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REVIEW ARTICLE

A Unified National Inventory of Geological Heritage in Portugal: An Essential Tool for Geoconservation

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Abstract
National geoheritage inventories constitute fundamental tools for geoconservation, providing the scientific basis for the identification, assessment, management, and protection of geological heritage. In Portugal, two independent national inventories were developed during the last two decades by the University of Minho (UMinho) and by the Portuguese Geological Survey (LNEG), resulting in partially overlapping databases with different structures and territorial coverage. This paper presents the development of a unified National Inventory of Geological Heritage (NIGH), created through the merging, harmonisation, and expansion of these two previous initiatives. The methodology involved a comparative analysis of both inventories, the development of a relational database, the standardisation of data fields, GIS-based georeferencing, and the implementation of an online dissemination platform within the LNEG GeoPortal. The resulting inventory currently comprises approximately 400 geosites distributed across mainland Portugal and the two Autonomous Regions of the Azores and Madeira, organised into 26 geological frameworks representative of the country's geodiversity and its geological evolution. The database stores detailed information on geological characteristics, scientific relevance, conservation status, vulnerability, and management requirements, while ensuring ongoing updating through the participation of experts coordinating the different geological frameworks. The NIGH represents the most comprehensive national geoheritage database developed in Portugal to date and provides an essential tool for geoconservation, spatial planning, environmental management, research, education, and geotourism. Remaining challenges include geosite delimitation, legal protection, institutional integration within conservation policies, and the long-term sustainability of the inventory. The NIGH establishes a robust foundation for the future development of proactive geoconservation strategies in Portugal.

Keywords Geosites · geoheritage · inventory · geological frameworks · geoconservation

Introduction

Since the 1990s, geoconservation has progressively gained recognition within the Portuguese geoscientific community. Early discussions consistently highlighted a critical limitation: the absence of a coherent national strategy for the

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identification, assessment, and protection of geological heritage (Brilha 2005). Central to this limitation was the lack of a comprehensive and widely accepted national inventory, widely recognised as the essential foundation for any effective geoconservation framework (Brilha et al. 2010).

In response, two national-scale initiatives were developed during the 2000s, each addressing this gap from distinct conceptual and methodological perspectives: the Geo-Sítios database maintained by the National Laboratory of Energy and Geology (LNEG, Portuguese Geological Survey) (Ramalho 2005) and the National Inventory of Geosites coordinated by UMinho with the participation of the geoscientific Portuguese community (Brilha et al. 2010).

The LNEG Geo-Sítios online database was designed as a broad and inclusive catalogue of geosites, encompassing multiple types of value, including scientific, educational, touristic, cultural, and aesthetic dimensions. Its methodology is largely based on expert-driven site identification and qualitative assessment, resulting in a flexible and accessible database with territorial coverage of mainland Portugal. This inclusiveness was accompanied by a predominantly qualitative assessment approach, which constrained its use in decision-making processes requiring quantitative prioritisation and comparison among geosites.

The inventory coordinated by UMinho adopted a more restrictive and methodologically rigorous approach, focusing exclusively on the scientific value of geosites as the primary criterion for their identification. Grounded on ProGEO (International Association for the Conservation of Geological Heritage) and IUGS (International Union of Geological Sciences) guidelines, this inventory introduced a systematic framework based on thematic categories representing national geodiversity and supported by both qualitative characterisation and quantitative assessment procedures (Brilha et al. 2005, 2008; Brilha 2010). This approach enhanced comparability and scientific robustness but resulted in a more selective dataset of geosites of national and international relevance.

Although both initiatives represented significant advances for geoconservation in Portugal, their coexistence has introduced structural inconsistencies that have limited their practical effectiveness. The two inventories were characterised by differing objectives, selection criteria, and evaluation methodologies, leading to fragmentation in the recognition and use of geological heritage data in Portugal. This fragmentation was reflected in inconsistencies in geosite designation, duplication or omission of sites, and uncertainty among key stakeholders, including public authorities, environmental consultants, educators, and local communities. Consequently, the absence of a unified and operational framework has hindered the effective integration of geological heritage into spatial planning, environmental assessment, and geoconservation policies.

To address this limitation, a single database was proposed to integrate both inventories. The merging process required more than a simple aggregation of existing datasets; it demanded a critical reconciliation of their underlying conceptual models and methodological approaches. In this context, a coordinated effort was undertaken to develop a unified national inventory that integrated the strengths of both systems while minimising their respective limitations (Aires et al. 2025).

This paper presents the outcomes of this process and aims to: (i) define and justify the methodological procedures adopted for the integration of the two inventories; (ii) establish a harmonised and coherent set of geological frameworks representing Portugal's geodiversity; (iii) reassess previously inventoried geosites in order to establish a consistent classification of their relevance (local, national, or international); and (iv) consolidate a robust and operational geoconservation tool through the development of a georeferenced, open-access, and continuously updated database freely available online through the LNEG GeoPortal (https://geoportal.lneg.pt). By addressing long-standing inconsistencies in the national inventory framework, this work aims to contribute to strengthening the scientific basis and practical implementation of geoconservation in Portugal, while also providing a model that may be applicable to other countries facing similar challenges in harmonising geological heritage inventories.

Methods

Combination of Previous Inventories

The methodology adopted for merging the inventories involved a comparative analysis of the LNEG and UMinho databases, followed by their restructuring, modification, and expansion with the addition of new fields (Fig. 1A). This process included the review of duplicated geosites, the integration of shared information, and the incorporation of missing data. The main methodological steps comprised: (i) bibliographic research and analysis of other national inventories (Spain, Switzerland, and the United Kingdom); (ii) a detailed comparison of the structure, origin, organisation, and territorial coverage of both inventories, including the identification of overlapping geosites; and (iii) the development of a new database structure based on the LNEG inventory and expanded with additional fields.

The harmonisation process also addressed differences in geosite assessment between the two inventories. The UMinho inventory included both qualitative and quantitative

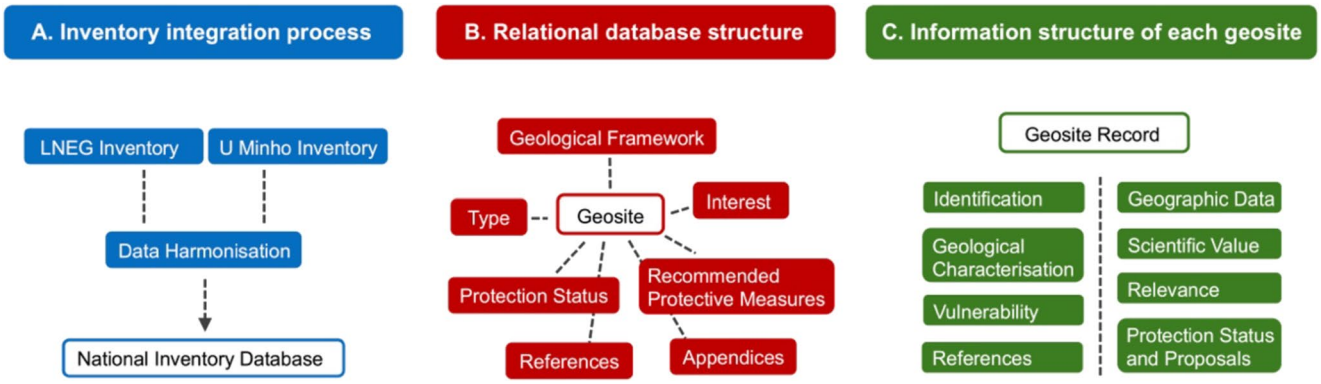


Fig. 1 Methodological framework adopted for the development of the new Portuguese National Inventory of Geological Heritage (NIGH). The workflow included the integration of the previous national inventories (**A**), the development of a relational database centred on the geosite entity (**B**), and the organisation of geological, geographic, conservation, and management information for each inventoried geosite (**C**)

assessments, whereas the LNEG inventory relied on qualitative expert assessment. For geosites represented in both inventories, the corresponding qualitative assessments were compared and were found to be generally consistent. Where discrepancies occurred, priority was given to the assessment from UMinho inventory because it had been produced using a more systematic and explicitly defined methodological framework. Quantitative scores already available in UMinho inventory were retained as such and were not derived from, or directly converted from, the qualitative assessments of the LNEG inventory. Geosites originating exclusively from the LNEG inventory retained their qualitative assessment and were not retrospectively assigned quantitative scores.

The resulting database preserves the relevant information from the original inventories, maintaining methodological specificities - such as the quantification of scientific value and vulnerability where available - while incorporating new fields relevant to geosite management, including geosite delimitation (Aires 2023). The new version made available through the GeoPortal includes only a subset of the complete database fields, whereas full access is restricted to thematic coordinators responsible for inventory management and the evaluation of new submissions. This approach aims to provide users with the most comprehensive inventory possible while ensuring a clear and streamlined presentation of information.

Database and GeoPortal Webpage

To support the merging of both inventories, a relational database was developed to integrate, harmonise, and standardise geological information (Fig. 1B). This solution enabled the consolidation of data from different sources characterised by distinct structures, objectives and methodologies, thereby ensuring the coherence, consistency and interoperability of the information. Simultaneously, it provided a structured platform for the organisation, management and dissemination of Portugal's geological heritage, establishing a robust foundation for future applications in research, spatial analysis, and geosites management. In parallel, a bilingual platform (Portuguese and English) was developed to make the inventoried information publicly available through the GeoPortal, ensuring open access, interoperability, and dissemination to different audiences, ranging from the scientific community to the general public.

The methodology adopted for developing the relational database comprised four main stages: (i) Structuring the database to integrate fields from existing inventories; (ii) Harmonisation and data loading; (iii) Georeferencing of geosites and development of the map; and (iv) Development of the dissemination platform. The database architecture was designed having future publication through the GeoPortal in mind, ensuring not only the robustness of the data model but also its suitability for access and use by different types of users. The database is organized into eight main entities (Fig. 1B): Geosite; Geological framework; Type (palaeontological, mineralogical, geomorphological, etc.); Interest (scientific, educational, touristic, cultural, ecological, aesthetic); Protection status; Recommended protective measures; Bibliographic references; and Appendices. These entities were structured according to database standardisation principles to ensure data integrity and minimise redundancy.

The harmonisation and data loading phase involved integrating information from the two original databases into a single, coherent and standardised model. This process included a comparative analysis of the existing structures, the identification of field correspondences, and the definition of transformation and standardisation criteria to ensure semantic and structural consistency, together with the reconciliation of the different assessment approaches described in Sect. 2.1. Each geosite was assigned to one or more of

the geological frameworks representative of the Portuguese geodiversity and its geological evolution. Following this stage, the data were uploaded into the new database while ensuring record integrity and the preservation of relevant information. Representative photographs and bibliographical references providing scientific support were also incorporated.

Georeferencing constituted an essential step, enabling the spatial representation of geosites within a GIS environment. Each geosite was georeferenced based on the coordinates of its central point, with validation and adjustment procedures carried out whenever necessary to ensure locational accuracy. Based on this information, the Geosite Map was developed, enabling a spatial analysis of the inventory.

The final stage involved the development of an open-access platform through the LNEG GeoPortal. The solution comprises three main components: an online database; an interactive map; and an application for mobile devices (Fig. 2). The online database enables users to access the various attributes of each geosite in an organised and structured manner, including descriptive information, thematic classifications, protection status, bibliographic references and multimedia elements (Fig. 1C). The interactive map, available through the Map Viewer, allows users to visualise, search, and analyse geosites, as well as integrate them with other geospatial information layers, with a particular focus on geological mapping. The application was developed to facilitate fieldwork and is optimised for mobile or small-screen devices. The dissemination of information through the GeoPortal ensures fundamental principles such as open access, interoperability and data standardisation, thereby promoting data reuse in multiple contexts.

Management

Like the previous inventory coordinated by the UMinho, the new NIGH follows a methodology adapted for national-scale inventories, originally defined by ProGEO and the IUGS. This methodology is based on the definition of geological frameworks corresponding to the principal themes that best represent the geological evolution of the Portuguese territory, encompassing topics related to both internal and external geodynamics. Within the new inventory, each geological framework is coordinated by three recognised experts responsible for maintaining the scientific reliability of the respective framework and for selecting the most scientifically relevant geosites. Increasing the number of coordinators per framework from one to three, compared with the former UMinho inventory, was intended to ensure a more transparent, balanced, and democratic process for geosite selection and characterisation. The use of three coordinators was also intended to avoid reliance on a single expert opinion and to facilitate balanced decision-making in cases of disagreement. No formal voting procedure was imposed, however, and each group determines its own decision-making process, with consensus being preferred whenever possible.

Accordingly, for each thematic category, a team of recognised specialists voluntarily contributed to validating the geosites considered most representative of each geological framework, subsequently updating their information and proposing new geosites. The assessment of new geosite submissions is also the responsibility of the coordinators of each geological framework. The collaboration of this multidisciplinary team of more than 60 national experts in the coordination of the new inventory provides the project with greater scientific rigor, methodological consistency and credibility, while ensuring the continuous updating and independent validation of its contents.

A total of 26 geological frameworks were defined within the inventory (Table 1), adapted from the 27 established in the previous UMinho inventory (Brilha et al. 2010). Most geological framework names were revised to harmonise and standardise nomenclature. In addition, two former frameworks related to coastal geomorphological heritage – "High

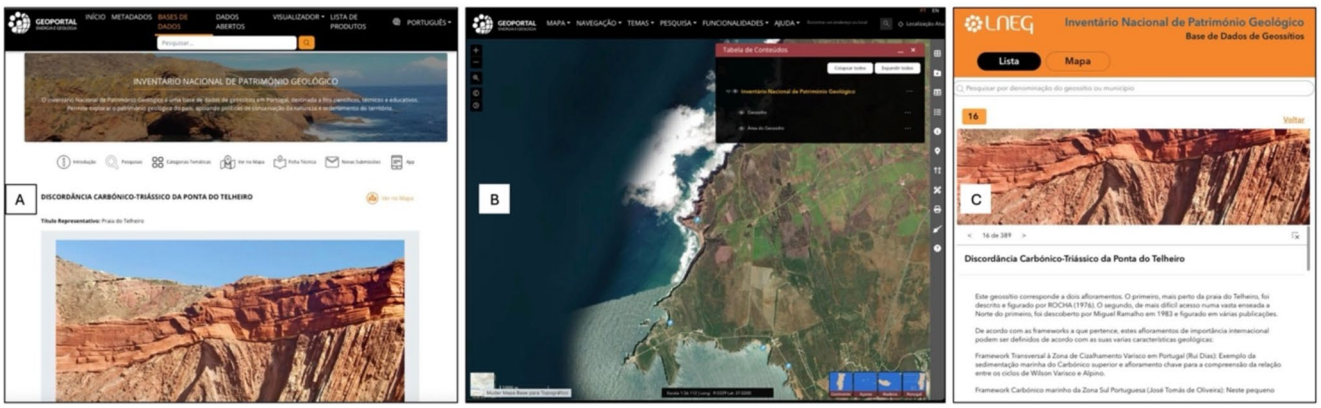


Fig. 2 Interfaces of the NIGH available at the LNEG GeoPortal, including the online database (**A**), interactive map viewer (**B**), and mobile application (**C**) with the example of the Ponta do Telheiro Unconformity geosite

Table 1 Geological frameworks adopted in the Portuguese National Inventory of Geological Heritage (NIGH), representing the principal themes of the geodiversity and geological evolution of Portugal

#	Geological Framework	Main Type of Geological Heritage	#	Geological Framework	Main Type of Geological Heritage
1	Neoproterozoic Basement of the Iberian Massif	Stratigraphical; Petrological	14	Triassic Record in the Lusitanian Basin	Stratigraphical; Petrology
2	Carbonate Palaeozoic Sequences in the Ossa-Morena Zone	Petrological	15	Jurassic Record in the Lusitanian Basin	Stratigraphical; Palaeontological
3	Ordovician Record in the Central-Iberian Zone	Stratigraphical; Palaeontological	16	Cretaceous Record in the Lusitanian Basin	Stratigraphical
4	Palaeozoic Record in the Ossa-Morena Zone	Palaeontological; Stratigraphical	17	Vertebrate fossils	Palaeontological
5	Exotic Terranes in Northeastern Portugal	Petrological; Tectonic	18	Meso-Cenozoic Record in Algarve	Stratigraphical
6	Variscan Tectonic Evolution	Tectonic; Stratigraphical	19	Cenozoic Basins	Stratigraphical; Palaeontological
7	Geology and Metallogeny in the Iberian Pyrite Belt	Mineralogical; Petrological	20	Iberian Massif Landforms and Fluvial Network	Geomorphological
8	Marine Carboniferous Record	Stratigraphical; Petrological	21	Karst Systems	Geomorphological; Hydrological
9	Continental Carboniferous Record	Stratigraphical; Petrological	22	Coastal environments and landforms	Geomorphological
10	Pre-Mesozoic granitoids	Petrological	23	Neotectonics Record	Tectonic; Geomorphological
11	W-Sn Mineralization	Mineralogical	24	Record of Pleistocene Glaciations	Geomorphological
12	Gold Mineralization	Mineralogical	25	Volcanism and Landforms in Azores	Volcanic; Geomorphological
13	Meso-Cenozoic Tectonic Evolution in the Western Iberian Margin	Tectonic; Stratigraphical	26	Volcanism and Landforms in Madeira	Volcanic; Geomorphological

Coasts" and "Low Coasts" – were merged into one entitled "Coastal landforms and environments".

The updating of the inventory relies on the active contribution of the geological community. An inventory of this nature can never be considered complete, as it must evolve continuously alongside advances in scientific knowledge. Consequently, the absence of geosites in a particular area may simply indicate that they have not yet been surveyed. Likewise, some sites may gain greater scientific relevance over time, while new geosites may be identified. The new inventory is therefore conceived as a dynamic and updateable inventory, open to new submissions from both specialists and the interested public. For this purpose, a submission form is available on the inventory website, and all proposals are subsequently assessed and validated by the coordinators responsible for the corresponding geological framework.

Results

Overview of the National Geological Heritage Inventory

The National Inventory of Geological Heritage currently includes approximately 400 geosites distributed across the 26 geological frameworks representing the geodiversity of mainland Portugal and the Autonomous Regions of the Azores and Madeira (Figs. 2 and 3). The inventory allows the incorporation of new geosites as well as the regular revision of existing records. This approach ensures that the inventory remains scientifically up to date and capable of reflecting advances in geological knowledge and geoconservation priorities. All submitted information is reviewed and validated by the coordinators responsible for each geological framework, thereby supporting scientific reliability, methodological consistency, and data quality. Each geosite is documented through a structured set of fields that includes information on geological characteristics, geographic location, scientific significance, conservation status, and vulnerability, providing a comprehensive basis for geoconservation, management, research, and public dissemination.

Geological Frameworks

The general characterisation of the scientific relevance of the 26 geological frameworks is presented in the following sections.

Neoproterozoic Basement in the Iberian Massif

Pre-Ordovician rocks occupy extensive areas of the central-western Iberian Peninsula (Portugal and Spain) and

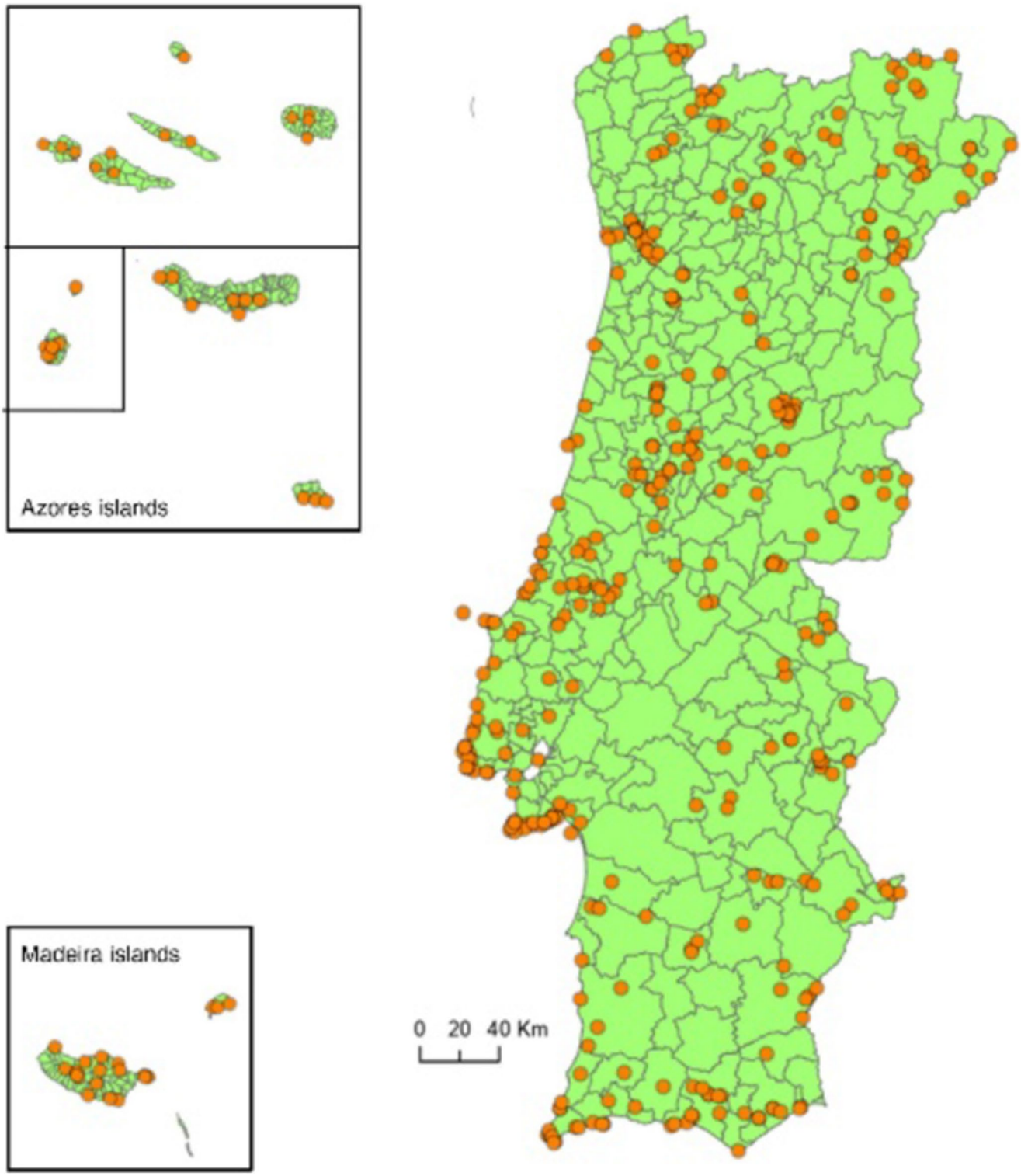


Fig. 3 Maps showing the distribution of approximately 400 geosites included in the NIGH

correspond mainly to Neoproterozoic–Lower Cambrian successions of the Central Iberian Zone (Tassinari et al. 1996). Traditionally grouped under the term "Schist-Greywacke Complex", these metasedimentary sequences comprise thick, predominantly pelitic and metagreywacke units underlying the Ordovician unconformity. Although long considered monotonous, recent studies reveal significant lithostratigraphic diversity, facies variability, and complex basin architectures. Sedimentation evolved from deep-marine turbiditic systems to shallower slope–platform environments during the early Cambrian, later overprinted by low-grade Variscan deformation and metamorphism (Oliveira et al. 2026). Facies distribution suggests highly subsident semi-graben basins with partly independent evolution, yet recording global tectonic, magmatic, and oceanographic events. These successions are fundamental for reconstructing the Iberian Cadomian belt along the northern Gondwana margin and for refining palaeogeographic links with Avalonia and Armorica. Their scientific importance makes them key targets for stratigraphic revision, geochronological studies, and geoheritage assessment within the Iberian Massif.

Carbonate Palaeozoic Sequences in the Ossa-Morena Zone

Palaeozoic marbles of the Ossa-Morena Zone form a heterogeneous set of carbonate outcrops extending from Elvas to Serpa. Collectively, they represent a long-lived regional carbonate platform initiated in the Early Cambrian under extensional tectonic conditions that persisted, intermittently, until at least the Middle Devonian. These successions are crucial for understanding the early stages of the Paleozoic Wilson Cycle in Iberia. In the Estremoz Anticline and Moura – Ficalho structures, quarrying has exposed exceptional natural cross-sections of stratigraphy, folding, ductile deformation, karstification, and later doleritic intrusions linked to post-Variscan extension (Carvalho et al. 2008). Economically, the Estremoz marble district is the most important, with centuries of extraction history, and remains active today. It has major cultural significance, having shaped architecture and regional identidy, which led to the recognition of Estremoz Marble as Heritage Stone by the Heritage Stone Subcommission of the International Union of Geological Sciences. The combination of scientific relevance, spectacular quarry exposures, industrial heritage, and internationally known ornamental stone resources makes these Palaeozoic marbles a key component of Portuguese geological heritage (Menningen et al. 2018; Moreira and Lopes 2019).

Ordovician Record in the Central-Iberian Zone

Ordovician strata of the Central Iberian Zone in Portugal comprise a diverse succession of sedimentary facies deposited along the margins of Gondwana, recording globally significant transgressive–regressive cycles, climatic warming episodes, and glaciomarine conditions. These sequences include the iconic Armorican Quartzite, fossiliferous shales, oolitic ironstones, and diamictites. Their scientific importance has been recognized since the nineteenth century through classic studies in Valongo Anticline and Buçaco Syncline, which yielded internationally significant collections of trace fossils and marine invertebrates now curated in Lisbon. Outstanding outcrops in North and Central Portugal preserve exceptional stratigraphic, palaeontological, geomorphological, and mining features (Sá et al. 2003; Gutiérrez-Marco et al. 2009; Pereira et al. 2015b). The widespread occurrence of *Skolithos* and *Cruziana* ichnofacies (Fig. 4A), together with resistant quartzite ridges forming remarkable landscapes, enhances their educational and scenic value. These attributes have supported geoconservation initiatives and geopark development, making the Portuguese Ordovician one of the most emblematic components of Portugal's geological heritage.

Palaeozoic Record in the Ossa-Morena Zone

The Ossa-Morena Zone (OMZ) is the southernmost hinterland domain of the Iberian Massif, preserving a significant stratigraphic, palaeontological, and magmatic record related with different stages of the Variscan Cycle. The Palaeozoic succession rests unconformably upon an Ediacaran succession and begins with Cambrian carbonate and volcano-sedimentary successions deposited during intracontinental rifting. These units include some of the oldest known fossiliferous assemblages in Portugal, notably the Marianian fauna of Vila Boim. The Cambrian-Ordovician break-up unconformity, associated with tholeiitic and alkaline magmatism, records the onset of the Rheic Ocean opening (Sánchez-García et al. 2010). Ordovician to Lower Devonian successions preserve outstanding sedimentary and palaeontological records of passive-margin conditions (Robardet and Gutiérrez-Marco 2004), including graptolite-bearing successions in the Barrancos region, a reference section for Silurian biostratigraphy. During the latest Early Devonian, sedimentation patterns changed, recording the transition to an active margin, and syn-orogenic sedimentation became dominant from the Middle Devonian to the Carboniferous. This sedimentation included both carbonate (e.g. Odivelas Limestones) and siliciclastic (e.g. Toca da Moura) deposits, being associated with contemporaneous orogenic volcanism (Oliveira et al. 2019).



Fig. 4 Examples of geosites: Penha Garcia Ichnological Park and Quartzite Ridge (**A**), "Pedras Parideiras" Local Natural Monument (**B**), Bajocian GSSP, Bathonian ASSP and the Cabo Mondego Geological Section (**C**), Ourém/Torres Novas Dinosaur Footprints Natural Monument (**D**)

Exotic Terranes in Northeastern Portugal

The Morais and Bragança Massifs in northeastern Portugal belong to a set of five allochthonous complexes in northwestern Iberia, within the Galicia Trás-os-Montes Zone. They preserve remarkable piggy-back thrust architectures composed of several superposed tectono-stratigraphic units, formed by obduction in an accretionary wedge, and later unrooted and stacked onto the Iberian autochthonous domain, the Central Iberian Zone, representing the Gondwana continent (Martínez-Catalán et al. 2019). The Morais and Bragança massifs preserve thrust-stack architectures composed of four tectonically juxtaposed units, which slid onto the autochthonous domain using a tectonic carpet of Variscan synorogenic marine sediments that currently defines the Lower Parautochthon. From base to top, the thrust pile of northeast Portugal includes slices of increasingly allochthonous units, namely (Marques et al. 1996; Mateus et al. 2016): (1) the Parautochthonous Thrust Complex, or Upper Parautochthon; (2) the Lower Allochthon (or Basal Unit); (3) the Middle Allochthon (or Ophiolite Unit); (4) the Upper Allochthon or Continental Allochthonous Terrane. This exceptionally preserved nappe-slice sequence makes northeastern Portugal one of the key areas for understanding Variscan tectonics and the processes related to the assembly of Pangea.

Variscan Tectonic Evolution

The Iberian Peninsula is a key region for understanding the pre-Mesozoic evolution of the northern margin of Gondwana. Its complex geodynamic history reflects the superposition of Ediacaran Cadomian subduction (Alvaro et al. 2026), Lower Palaeozoic extensional tectonics, and the Upper Palaeozoic Variscan Orogeny (Simancas 2019). The distinctive stratigraphic, tectono-metamorphic, and magmatic features of the Iberian Massif allow the recognition of several tectonostratigraphic zones (Dias et al. 2016), providing one of the most complete geotransects of the European Variscan Belt, extending from Cantabria (northern Spain)

to Algarve (southwest Portugal). Indeed, Portugal offers an exceptionally well-exposed cross-section of the Variscan Belt. In southern Alentejo and Algarve (South Portuguese Zone), Carboniferous sedimentary rocks affected by low- to very low-grade metamorphism are widely exposed and represent the foreland fold-and-thrust belt. In contrast, the hinterland domains (Central Iberian and Ossa-Morena zones) are mainly composed of Lower Palaeozoic successions that experienced higher metamorphic grade (Dias da Silva et al. 2023), being intruded by extensive Late Palaeozoic granites. This outstanding geological framework provides exceptional scientific and educational value, allowing an improved understanding of Variscan and Cadomian tectonics and the assembly of the supercontinent Pangaea.

Geology and Metallogeny in the Iberian Pyrite Belt

The Iberian Pyrite Belt is a world-class geological province and the largest known concentration of volcanogenic massive sulphide (VMS) deposits on Earth. Pre-mining resources exceeded 1,750 Mt of ore containing extraordinary amounts of Cu, Zn, and Pb, surpassing all other VMS provinces worldwide. Other mineralization includes Fe-Mn oxides and late variscan Cu, Ba-Pb, Sb (Au) dikes (Oliveira et al. 2013). Iconic VMS deposits such as Rio Tinto, Aljustrel, and Neves-Corvo rank among the largest and richest of their type, with exceptionally high copper and tin grades. Hosted by a well-preserved Upper Devonian–Lower Carboniferous volcano-sedimentary succession, the belt records massive sulphides and stockwork mineralization formation in pull-apart basins related to Variscan tectonics following ocean closure. Outstanding natural and mining exposures, including open pits and underground sections in Portugal and Spain, reveal volcanic architecture, hydrothermal alteration, sedimentation, deformation, and mineralisation processes with remarkable clarity. Its continuing scientific relevance, mining heritage, and growing geoconservation initiatives make the belt a key international geoheritage region, with outstanding Portuguese examples including the Aljustrel, São Domingos, and Lousal mines (Relvas et al. 2012; Matos and Pereira 2024).

Marine Carboniferous Record

The South Portuguese Zone (SPZ) preserves an exceptional record of Carboniferous marine sedimentary sequences linked to the evolution of the Variscan foreland margin. Four principal domains are recognised within the SPZ, also encompassing Devonian sequences: the Pulo do Lobo, the Iberian Pyrite Belt, the Baixo Alentejo Flysch Basin, and the Southwest Sector (Oliveira et al. 2019; Pereira et al. 2018, 2023). During the Late Devonian-Early Carboniferous, an epicontinental sea evolved into an extensional basin marked by intense submarine bimodal volcanism, generating the Volcano-Sedimentary Complex of the Iberian Pyrite Belt and its world-class massive sulphide deposits. From the late Visean onwards, Variscan compression inverted this basin, uplifted volcanic terrains, and triggered deposition of thick turbiditic successions in a southwestward-prograding foreland basin represented by the Mértola, Mira, and Brejeira formations, all included in the Baixo Alentejo Flysch Group. In the Southwest Sector, mixed siliciclastic-carbonate platform sedimentation persisted until final basin drowning. These well-exposed successions, later deformed under low-grade metamorphic conditions, provide key evidence for tectonic inversion, basin migration, ore genesis, and foreland sedimentation during assembly of Pangea.

Continental Carboniferous Record

In the Iberian Massif, Carboniferous sedimentation is represented by syn- and post-orogenic successions deposited under tectonically unstable conditions related to folding and uplift during the Variscan Orogeny. Although Carboniferous rocks crop out widely across the Iberian Peninsula, the most complete marine successions are restricted to the external domains of the massif, namely the Cantabrian Zone and the South Portuguese Zone, which formed frontal sectors of the orogen and major depocentres for erosional detritus. In contrast, emerged internal domains hosted intramontane basins during the Pennsylvanian, especially during the Stephanian (Gzhelian), filled with alluvial, fluvial, lacustrine, and palustrine deposits representing the molasse of the waning mountain belt. In Portugal, these continental upper Carboniferous successions occur in three main areas: the Porto region along the Douro-Beiras shear zone (Correia et al. 2018), the Buçaco Basin (Machado et al. 2018) near Coimbra, and the Santa Susana Basin (Wagner and Lemos de Sousa 1983), providing key evidence of late Variscan tectonics and post-orogenic landscape evolution.

Pre-Mesozoic Granitoids

The pre-Mesozoic granitoids of the Central Iberian and Ossa-Morena Zones record the geodynamic evolution of the Iberian Massif from Cadomian crustal processes to the Variscan Orogeny. Their emplacement was controlled by major tectonic structures, particularly the Porto–Tomar–Badajoz–Córdoba shear zone, during collisional and post-collisional magmatic episodes from the Carboniferous to the Permian (Sant'Ovaia et al. 2024). Distinct granitoid generations display contrasting petrographic, geochemical, and isotopic signatures, reflecting crustal melting, mantle input, and magma hybridization (Ferreira et al. 2026). Representative

massifs in northern and southern Portugal provide evidence of crustal growth, deformation, and lithospheric reworking during Paleozoic orogenesis. Beyond their scientific importance, these granitoids have long been used as building and ornamental stones, shaping monuments, urban landscapes, and vernacular architecture (Almeida 2024). Their diversity, distribution, economic relevance, and cultural legacy justify their recognition as a major category of Portuguese geoheritage. This thematic category currently includes 18 geosites across mainland Portugal and the Berlengas archipelago, illustrating remarkable petrological, structural, and geomorphological diversity, including ring complexes and magma-mixing features. Key examples include the iconic nodular granites of the "Pedras Parideiras" in Arouca (Fig. 4B).

W-Sn Mineralization

Portuguese tin (Sn) and tungsten (W) deposits are part of the Iberian W–Sn metallogenic province, extending from Galicia into central Spain through northern and central Portugal. Mainly sited within the Galicia–Trás os Montes and Central Iberian Zones, these deposits are intimately associated with Variscan granites emplaced into thick pre-Mesozoic metasedimentary sequences (Losantos et al. 2025). Tin mineralization typically develops in (aplite-)pegmatites and quartz veins, whereas tungsten is predominantly hosted in hydrothermal quartz veins and, locally, in skarns. These ore-systems record the interplay between granite emplacement, magmatic differentiation, (magmatic-)hydrothermal fluid evolution, and a varied array of structural controls (Romer and Kroner 2016). They are internationally significant for understanding granite-related metallogeny and crustal fluid circulation during the late stages of Variscan orogenesis (Borrajo et al. 2024). Many sites preserve exceptional outcrops of lodes and their typical mineral assemblages, along with historic underground mining works; scheelite-bearing veins are particularly valued for educational purposes due to their distinctive luminescence under UV light. The scientific, historical, and mining heritage value of Portuguese Sn–W deposits makes them a key component of national geoheritage, illustrating the tight links between tectonics, magmatism, mineral resources, and industrial development.

Gold Mineralization

The main gold districts of Portugal, including Três Minas and the Dúrico-Beirão Mining District, constitute outstanding records of Variscan metallogenesis and ancient mining heritage. Located within the Central Iberian and Galicia–Trás-os-Montes domains, these districts host structurally and lithostratigraphically controlled Au–Sb and Au–As mineralisation associated with shear zones, quartz veins, granites, volcanic rocks and silicified metasediments. Três Minas preserves one of the largest Roman open-pit gold mining complexes in Europe, where exploitation followed major tectonic lineaments and hydrothermal ore zones (Noronha et al. 1998). The Dúrico-Beirão district records multiple mineralising events, from Palaeozoic syngenetic enrichments to Variscan hydrothermal systems and later Alpine remobilisation (Couto et al. 2016; Couto and Roger 2017). These deposits are of exceptional scientific value for understanding ore-forming processes, structural and lithostratigraphic controls, and the relationship between magmatism and mineralisation in the Iberian Massif. Their archaeological remains, historical exploitation, and imprint on the landscape also confer high cultural significance, making these districts key components of Portuguese mining geoheritage and significant geosites for research, education, and geotourism.

Meso-Cenozoic Tectonic Evolution in the Western Iberian Margin

The Western Iberian Margin (WIM) is a passive Atlantic-type margin whose evolution records key stages of the Alpine cycle, from the initial opening of the North Atlantic to later compressional reactivation. During the Late Triassic–Early Cretaceous, crustal stretching generated several non-volcanic rift basins, including the Lusitanian, Alentejo and Algarve basins, followed by continental breakup and oceanic crust formation between Iberia and North America (Kullberg et al. 2014; Terrinha et al. 2019). In Portugal, the Lusitanian Basin offers exceptional onshore exposures due to Cenozoic tectonic inversion linked to Africa–Eurasia convergence. Widespread salt tectonics associated with the Hettangian Dagorda evaporites produced numerous diapiric structures and had an important role in basin inversion. The WIM geological record also preserves Late Cretaceous alkaline magmatism (e.g., Sintra, Sines, Monchique), interpreted as related to major lithospheric lineaments (Miranda et al. 2009). Controlled by inherited Variscan faults, these basins document repeated rifting phases, variable subsidence, inversion structures, and magmatic intrusions. Owing to its outstanding preservation, the Western Iberian Margin is a key natural laboratory for tectonics, basin evolution, and geoheritage studies.

Triassic Record in the Lusitanian Basin

The Upper Triassic–Lower Jurassic successions of the Lusitanian Basin and Algarve Basin record two major, approximately orthogonal rift systems developed along the southwestern margin of Iberia during the breakup of Pangea. Since the Late Triassic, continental extension and

tectonic subsidence generated half-graben basins filled by coarse alluvial fan, fluvial, lacustrine, and distal siliciclastic deposits, later evolving to widespread evaporitic environments with halite and anhydrite under hot, seasonally arid climates (Soares et al. 2012). These successions, which record different palaeoenvironments and depositional histories in the two basins, document the transition from intracontinental rifting to early marine incursions in the Hettangian. Volcanic and volcaniclastic deposits, especially in the Algarve Basin, are linked to the Central Atlantic Magmatic Province, a key stage in Central Atlantic opening. Detailed stratigraphic, sedimentological, palynological, and basin-analysis studies (Ruciński et al. 2026; Vilas-Boas et al. 2026) make these sequences internationally significant archives for understanding Pangea fragmentation, early Atlantic evolution, and Triassic to Jurassic paleoenvironmental change. Their scientific importance and excellent exposures justify their recognition as a valuable component of Portuguese geoheritage.

Jurassic Record in the Lusitanian Basin

The Jurassic of Portugal is exposed in two major sedimentary basins, the Lusitanian Basin and the Algarve Basin, with the Lusitanian record being among the most complete in Europe, spanning the Hettangian to Tithonian. These successions are fundamental for reconstructing pre-, syn-, and post-rift evolution linked to the opening of the North Atlantic. Exceptional coastal exposures provide world-class reference sections, notably Cabo Mondego (Fig. 4C), which hosts the Bajocian GSSP (Pavia and Enay 1997) and the Bathonian ASSP (Fernández López et al. 2009), and Peniche, where the Toarcian GSSP was established (Rocha et al. 2016). Peniche also preserves one of the best global records of the Early Toarcian Oceanic Anoxic Event. Other key regions (sections or sites), including São Pedro de Moel, Rabaçal, Barranco do Zambujal/Fórnea, Baleal, Cabo Espichel, and Lourinhã, document diverse marine to continental environments, namely carbonate ramps, reefs, deltaic systems, and rich fossil assemblages. Their outstanding stratigraphic continuity, palaeontological richness, and international correlation value make the Portuguese Jurassic a cornerstone of national geoheritage and global Jurassic research.

Cretaceous Record in the Lusitanian Basin

Cretaceous sediments of western Portugal crop out from Aveiro to Setúbal and provide an exceptional record of Atlantic-margin evolution. The succession is mainly siliciclastic, ranging from fluvial to shallow-marine depositional systems, with locally well-developed open and restricted carbonate platforms. Stratigraphic architecture reflects three major phases of Central and North Atlantic opening, expressed by regional unconformities and alternating progradational–retrogradational facies successions (Dinis et al. 2008). Marked north–south contrasts, separated near Caldas da Rainha, document differential subsidence and basin reorganisation (Rey and Dinis 2004). Southward, thicker Berriasian–Cenomanian successions occur near Lisbon, where Cenomanian rudist limestones became important building stones (Callapez 2004). Coeval magmatism is represented by the Sintra pluton and Lisbon–Mafra volcanic complexes. Northern sectors preserve mainly post-lower Cenomanian strata, including extensive Cenomanian–Turonian carbonate platforms and younger fluvial to marginal-marine deposits linked to tectonic inversion and drainage reorganisation. Key geosites include the coastal cliffs of Ericeira and Cascais, Nazaré lighthouse, and Cabo Espichel, renowned for Lower Cretaceous dinosaur trackways and outstanding sedimentological exposures.

Vertebrate Fossils

Portugal possesses an exceptional vertebrate palaeontological heritage, remarkable for both taxonomic diversity and density of fossil localities, with more than 330 known sites. Fossil occurrences range from the Early Devonian to the Holocene, although the richest record is concentrated in the Lusitanian, Lower Tagus, and Algarve basins (Figueiredo et al. 2023; Pimentel et al. 2025). Special attention is given to type-localities where more than 200 vertebrate type specimens were collected. The Upper Jurassic is particularly significant, notably the Guimarota coal mine and the Lourinhã Formation, which have yielded world-class assemblages of mammals, dinosaurs, crocodylomorphs, pterosaurs, eggs, and trackways (Rotatori et al. 2025). Other key sites include the Eocene locality of Silveirinha, rich in terrestrial vertebrates, and the Miocene coastal deposits of Almada–Sesimbra, renowned for fishes and marine mammals. Portugal also preserves outstanding ichnological geosites, including extensive dinosaur tracksites at Pedreira do Galinha (Fig. 4D), Vale de Meios, Cabo Espichel, and Carenque. This combination of body fossils, trace fossils, and long stratigraphic continuity makes Portugal a region of international relevance for vertebrate evolution, palaeoecology, and geoheritage conservation.

Meso-Cenozoic Record in Algarve

The Algarve region of southern Portugal lies closest to the eastern sector of the Azores–Gibraltar Fracture Zone and preserves an outstanding record of Atlantic–Mediterranean geodynamic evolution. Three main geomorphological

domains are recognised: the Serra Algarvia, underlain by Variscan basement; the Barrocal, dominated by Mesozoic carbonate formations; and the coastal belt, where Mesozoic rocks prevail in the west and Cenozoic deposits in the east. Karst landscapes are widespread in the Barrocal and the coastal belt, while Holocene estuarine and barrier island systems overlie younger Neogene and Quaternary sediments. The Algarve Basin developed along the margin of the Iberian Massif during the opening of the Tethys and North Atlantic oceans. Upper Triassic to Lower Jurassic red beds and evaporites record continental rifting deposits associated with the breakup of Pangaea (Vilas-Boas et al. 2024; Ruciński et al. 2026). This phase culminated in the mafic igneous activity of the Central Atlantic Igneous Province. The Jurassic platform carbonates, rich in fossils, provide key palaeoenvironmental and palaeoclimatic information, whereas alternating carbonate and siliciclastic Cretaceous successions record sea-level fluctuations and Iberian palaeogeographic evolution (Mendes et al. 2023). Late Cretaceous magmatism is represented by the Monchique nepheline syenite massif. Miocene warm-water carbonates and later fluvial-to-nearshore deposits document progressive continentalisation and major climatic change.

Cenozoic Basins

The Iberian Mesozoic–Cenozoic transition records a major tectonic shift from North Atlantic–related extension to Alpine compression linked to Eurasia–Africa convergence. In Portugal, this produced reliefs and sedimentary basins whose discontinuous successions record successive tectonic phases. Basin differentiation began with Paleogene fault reactivation and intensified in the Neogene. Tortonian uplift of the Central Range separated the Mondego and Lower Tagus, the two main Portuguese Cenozoic basins. Their continental to marine successions record palaeogeographic, tectonic, climatic and eustatic change in western Iberia. In the Lisbon–Setúbal area, high-resolution stratigraphy, rich fossil assemblages, isotopic dating and palaeomagnetism provide key archives of Neogene evolution along the North Atlantic margin (Pais et al. 2012; Cunha 2019). Over 150 papers published in the past decade highlight the high Cenozoic palaeobiodiversity of the Lower Tagus and Mondego basins. The Lower Tagus yields Miocene invertebrates and vertebrates, notably elasmobranchs, crocodylomorphs and cetaceans, whereas Mondego palaeofloras and micromammals document the Pliocene climatic transition. Recent taxonomic revisions have refined regional biostratigraphy and wider Palaeogene–Neogene paleoclimatic correlations.

Their scientific importance, excellent exposures and international stratigraphic value make these basins central to Portuguese geological heritage.

Iberian Massif Landforms and Fluvial Network

The Iberian Massif forms the oldest and most rigid core of Iberia, composed mainly of Proterozoic–Palaeozoic metasedimentary rocks and abundant granitoids affected by Variscan and Alpine deformation. Long-term denudation since the Variscan Orogeny generated the extensive Iberian Meseta, a high planation surface later deeply incised by major river systems. Differential erosion of resistant quartzites, schists, and granites produced characteristic Appalachian-type relief with NW–SE quartzite ridges and broad erosion surfaces. Subsequent Alpine tectonics reactivated inherited structures, uplifting mountain ranges such as Serra da Estrela and creating fault-bounded depressions, escarpments, and intramontane basins (Galve et al. 2020). Cenozoic sedimentary basins preserve key records of tectonic pulses, drainage reorganisation, and climatic change, while Quaternary river terraces document regional uplift and palaeoenvironmental evolution (Cunha et al. 2019). This exceptional geomorphological diversity makes the Iberian Massif a fundamental natural archive for understanding long-term landscape evolution, tectonic inheritance, and climate–surface interactions. Its planation surfaces, structural landforms, sedimentary basins, and fluvial systems (Fig. 5A) represent a major component of Portuguese geoheritage (Pereira et al. 2015a).

Karst Systems

Portugal's limestone regions are mainly distributed along a coastal belt extending from the central-north to the south of the country and contain some of its most significant karst landscapes. Although many areas have been affected by urbanisation, quarrying, infrastructure development, and land-use change, they preserve outstanding geomorphological and hydrological heritage. Most karst systems were developed in Mesozoic limestones, especially Jurassic formations of the Lusitanian and Algarve basins, but there are also very interesting examples in Cretaceous, Miocene, and locally Palaeozoic carbonates. The Estremadura Limestone Massif is the most extensive karst area, displaying poljes, dolines, lapiaz fields, caves, springs, and tectonically controlled escarpments (Rodrigues 2020). Other notable regions include the Sicó–Alvaiázere massif, Arrábida, Peniche, and coastal headlands (Fig. 5B) where marine erosion and karstification interact (Moura et al. 2006). In the Algarve, mesa reliefs, poljes, canyon valleys, megalapiaz, and major karst aquifers are particularly representative. These karstic landscapes also host important archaeological sites, subterranean ecosystems, and water resources, highlighting their high scientific, educational, and geoheritage value.



Fig. 5 Examples of geosites: Pulo do Lobo Waterfall and Fluvial Terrace (**A**), Ponta da Piedade coastal cliffs (**B**), Zêzere river glacial valley (**C**), Pico Mountain (**D**)

Coastal Environments and Landforms

Mainland Portugal has over 900 km of coastline, defined in a wide range of lithologies grouped into five tectonostratigraphic units. It exhibits remarkable geomorphological diversity, including extensive sandy beaches backed by dunes, rocky coasts with low and high cliffs, wave-cut platforms, pocket beaches, headlands and bays, estuaries, coastal lagoons, and barrier systems (Ferreira and Matias 2013). Large estuaries such as the Tagus and Sado, and lagoonal environments such as the Ria de Aveiro and Ria Formosa, host most of the coastal wetland areas. The western coast is strongly exposed to North Atlantic wave energy, resulting in active cliffs and widespread erosion (Ponte Lira et al. 2016), whereas the southern coast (Algarve), sheltered from northern and north-western waves, exhibits a low-to-moderate energy regime and a mixed morphology, including rocky promontories, sandy embayments and barrier islands. The interplay of geology, sea-level change, sediment supply, climate, and coastal dynamics makes Portugal an outstanding natural laboratory for the study of coastal geomorphology. Although densely populated and economically important due to tourism, ports, industry and urban development, nearly half of the coastline belongs to protected natural areas. The Portuguese coast's scientific relevance, scenic quality, ecological richness, and high sensitivity to climate change and erosion position it as one of the most valuable components of national geoheritage.

Neotectonics Record

Within this framework, neotectonics refers to tectonic deformation since the establishment of the present stress regime, approximately from the Piacenzian (~3 Ma) to the present. In mainland Portugal, situated on the Eurasian Plate (Iberian microplate) near the Eurasia–Nubia boundary along the eastern Azores–Gibraltar zone, ongoing NW–SE convergence (~4–5 mm/yr) generates low to moderate seismicity, punctuated by rare major earthquakes such as the 1755 event (Custódio et al. 2015). Active deformation mainly results

from reactivation of pre-existing Variscan, Mesozoic, and Cenozoic faults, producing reverse faults trending E–W to NE–SW and left-lateral strike-slip faults trending N–S to NNE–SSW. Long-term slip rates are generally low (0.005 to 0.5 mm/yr), and Quaternary erosion commonly obscures recent tectonic evidence, making clear surface expressions of active faulting scarce (Cabral 2012, 2019). Consequently, geological outcrops preserving neotectonic deformation are rare and highly valuable geosites, essential for understanding recent landscape evolution, active tectonic processes, and seismic hazard assessment in Portugal.

Record of Pleistocene Glaciations

Portugal's glacial and periglacial geoheritage occurs in the Serra da Estrela and the mountains of Minho, where landforms and deposits developed during Quaternary cold climates are preserved. These include U-shaped valleys, hanging valleys, glacial cirques, polished and striated bedrock surfaces, moraines, tills, and cryoclastic accumulations, documenting low-altitude and precipitation-driven glaciations. Systematic research since the 1970s based on the distribution and state of degradation of glacial deposits has allowed the extent of former glaciers to be established. More recent chronological approaches have constrained glacial development during two glaciations, highlighting the high scientific relevance of these features (Vieira et al. 2021; Pereira et al. 2022; Figueira et al. 2025). Approximately forty geosites were inventoried using criteria such as representativeness, rarity, integrity, and scientific knowledge, leading to the selection of key sites of national and international significance. In Serra da Estrela, notable examples include the Zêzere glacial valley (Fig. 5C), Covões de Loriga, Lagoa Seca, and Lagoa Comprida. In northern Portugal, important sites occur in the Peneda, Gerês, and Cabreira mountains, where cirques, moraines, erratic boulders, and subglacial deposits are well preserved.

Volcanism and Landforms in Azores

The Azores archipelago displays exceptional geodiversity (Nunes 2023) resulting from its unique geodynamic setting at an active triple junction plate boundary (Marques et al. 2025). The nine islands preserve a wide range of volcanic rocks and products, from mafic to silicic compositions, including lava flows, pyroclastic fall and flow deposits, and some local marine sediments and fossiliferous deposits, which record several eruptive episodes, sea-level changes, tectonic movements and erosional processes. Major landforms include polygenetic volcanoes, most of them with summit calderas, active fissure systems, monogenetic volcanoes, volcanic caves (lava tubes and pits), hydrothermal areas, graben structures, and spectacular coastal landforms such as old sea cliffs, lava deltas and detritus coastal platforms. Furnas caldera (S. Miguel) hosts diverse fumarolic fields and mineral waters, Pico Mountain volcano (Fig. 5D) is the highest mountain in Portugal, with outstanding basaltic volcanic landscapes, whereas Capelinhos volcano (Faial) reflects an iconic twentieth-century submarine eruption. The surrounding sea floor, including several seamounts and the Mid-Atlantic Ridge and its deep hydrothermal systems, further enhances the scientific significance of the Azores Islands (Zanon et al. 2023). Altogether, these attributes make the Azores a world-class natural laboratory for volcanology, tectonics, geodiversity and geoconservation.

Volcanism and Landforms in Madeira

The Madeira Archipelago, comprising Madeira, Porto Santo, the Desertas and Selvagens islands, represents an outstanding volcanic region of the Macaronesia biogeographical province, located on the African (Nubian) Plate. Madeira Island is the emergent summit of a large oceanic shield volcano built through successive submarine, subaerial, and post-erosional volcanic stages from the Miocene to the Holocene (Brum da Silveira et al. 2010). Its stratigraphy records alkaline lava flows, pyroclastic deposits, intrusive bodies, uplifted marine fossiliferous sediments, and widespread mass-movement deposits, illustrating the evolution of ocean-island volcanism (Ramalho et al. 2015; Martí et al. 2018). Porto Santo preserves an older and deeply eroded volcanic edifice, with differentiated magmatic rocks and remarkable marine and aeolian carbonate deposits. The archipelago also displays spectacular geomorphological features, including constructive volcanic landforms (e.g. scoria cones, lava deltas), deeply incised fluvial valleys, high sea cliffs and mass-wasting scarps. Owing to its exceptional geodiversity, scientific importance, scenic value, and well-developed geoconservation policies, the Madeira Archipelago constitutes an important natural laboratory for volcanology, island evolution, and geological heritage studies.

Discussion

The unified NIGH represents a major step forward for geoconservation in Portugal, as the merging of the two previous inventories consolidated dispersed information into a single coherent structure, reducing duplication while preserving the methodological specificities and scientific contributions of both projects. This integration also enabled broader territorial coverage and the harmonisation of nomenclature, thematic frameworks, and data organisation, thereby

facilitating the management, dissemination, and future updating of geological heritage information at the national scale.

Another important advantage of the new inventory lies in its institutional integration within LNEG, the Portuguese Geological Survey. Hosting the inventory within the national geological institution provides long-term institutional stability, technical capacity, and credibility, supporting its continuity beyond the duration of individual research projects. Geological surveys play a central role in the inventorying and management of geoheritage in several countries, as they possess the scientific expertise, cartographic resources, and national territorial perspective necessary for coordinating large-scale geoconservation initiatives. Furthermore, the integration of the inventory into the LNEG GeoPortal increases the accessibility and visibility of geological heritage information for researchers, decision-makers, municipalities, protected area managers, geoparks, and the general public.

The establishment of a comprehensive national geological heritage database constitutes an essential tool for the development of proactive geoconservation policies. Beyond its scientific value, the inventory provides a robust basis for land-use planning, environmental impact assessment, education, tourism, and territorial management. In particular, the systematic identification and characterisation of geosites allows decision-makers to recognise areas of geological significance that should be considered in planning and conservation processes. The availability of harmonised and georeferenced information also facilitates the integration of geoheritage into GIS and spatial planning instruments.

Despite these advances, several important challenges remain. One of the most significant is related to the official recognition of the inventory by the Institute of Nature Conservation and Forests (ICNF), the national authority responsible for nature conservation and protected areas in Portugal. Although the inventory represents a comprehensive, scientifically validated national database of Portuguese geological heritage, its effective integration into conservation policy and territorial planning instruments still requires institutional coordination and legal recognition. Strengthening collaboration between geological and environmental institutions will therefore be fundamental for ensuring that geological heritage becomes more effectively incorporated into national conservation strategies.

Another major challenge concerns the systematic delimitation and cartographic definition of geosite boundaries. While the current inventory includes the geographic location of geosites, many sites still require detailed delimitation based on geological, geomorphological, and management criteria. The definition of precise boundaries is particularly important for land-use planning, monitoring, legal protection, and vulnerability assessment. This issue becomes especially complex for extensive geomorphological landscapes, coastal systems, or geological structures with diffuse spatial limits. The progressive delimitation and cartographic representation of geosite boundaries is therefore considered a priority for the future development of the NIGH. This work will require field validation and the definition of boundaries based on geological and management criteria appropriate to each type of geosite. An initial attempt to obtain dedicated funding for this task was unsuccessful, and alternative funding opportunities are currently being explored.

The legal protection of geosites also remains a major challenge for geoconservation in Portugal. Although some inventoried geosites are located within protected areas, many significant sites still lack any statutory conservation status. The development of legal mechanisms specifically aimed at geological heritage protection remains limited when compared with biodiversity conservation frameworks. Consequently, the inventory may provide an important scientific basis for future strategies aimed at recognising and protecting geosites of high scientific, educational, or cultural value.

The relationship between NIGH and territorial stakeholders such as protected areas, municipalities, and UNESCO Global Geoparks also deserves particular attention. These entities play a crucial role in the management, interpretation, and promotion of geological heritage at the local and regional scales. Geoparks and municipalities have developed valuable local inventories and geoconservation initiatives that could contribute significantly to the ongoing improvement of the national inventory. The integration of local inventories would strengthen the representativeness and territorial comprehensiveness of the database, while simultaneously promoting collaboration between national and regional actors. Furthermore, the NIGH may support the development of thematic geotourism routes and educational initiatives that enhance the social and economic value of geoheritage.

The current set of 26 geological frameworks should not be regarded as a closed or definitive thematic structure. Some potential gaps have already been identified and remain under discussion, including the possible recognition of themes related to the history of geology and to soils. Other components such as slope processes, modern fluvial dynamics, and Quaternary stratigraphy and palaeoenvironmental records, are already represented to varying degrees within broader existing frameworks, though not systematically addressed as independent themes. The representativeness of these and other themes should be periodically reassessed. The dynamic nature of the NIGH allows not only the incorporation of new geosites but also the revision, subdivision,

or creation of geological frameworks whenever justified by advances in knowledge and improvements in the representativeness of the inventory.

Although the inventory already constitutes a robust national database, future work should also include more systematic assessments of global significance, particularly in accordance with international geoconservation methodologies and criteria. In this context, the future identification of potential Key Geoheritage Areas (KGAs) may provide an additional international framework for recognising areas that contain geoheritage of international scientific significance and for relating nationally inventoried geosites to broader global geoconservation priorities (Brilha et al. 2025).

Finally, the long-term sustainability of the inventory depends heavily on financial support and scientific engagement. At present, the maintenance and updating of the inventory rely largely on the voluntary collaboration of the geoscientific community. While this collaborative model demonstrates the strong commitment of these researchers, the absence of dedicated funding may limit the capacity for systematic updates, field validation, monitoring, and technological development. Similarly, maintaining the long-term motivation and active participation of researchers represents an ongoing challenge, particularly given the increasing administrative and academic demands placed upon scientists. Ensuring institutional support, financial resources, and formal recognition of contributions to the inventory will therefore be essential for supporting its future continuity and scientific robustness.

Conclusions

The unified National Inventory of Geological Heritage represents a significant milestone for geoconservation in Portugal, providing the first comprehensive and integrated national database of geological heritage. By merging the previous inventories coordinated by UMinho and LNEG, the project has consolidated dispersed information into a unified and standardised framework, ensuring greater territorial coverage, methodological consistency, and accessibility of geological heritage data.

The inventory currently includes around 400 geosites distributed across 26 geological frameworks representative of the geological evolution and geodiversity of the Portuguese territory, including mainland Portugal and the two Autonomous Regions of the Azores and Madeira. Its relational database structure and integration within the LNEG GeoPortal provide a robust platform for the management, dissemination, and ongoing updating of geological heritage information. The participation of more than 60 national experts in the coordination and validation processes further reinforces the scientific credibility and reliability of the inventory.

Beyond its scientific importance, the inventory constitutes an essential tool for geoconservation, territorial planning, environmental management, education, and geotourism. The availability of harmonised and georeferenced information facilitates the incorporation of geoheritage into spatial planning and conservation strategies, while also promoting public awareness of the Portuguese geodiversity. Nevertheless, important challenges remain. These include the official recognition of the inventory within national conservation policies, the delimitation and mapping of geosite boundaries, the continued assessment of thematic representativeness, the strengthening of legal protection mechanisms for geosites, and the establishment of stronger collaboration with protected areas, municipalities, and UNESCO Global Geoparks. The long-term sustainability of the inventory will also depend on continued institutional support, financial resources, and the active participation of the geoscientific community.

The National Inventory of Geological Heritage should therefore be regarded not as a final product, but as a dynamic and evolving instrument that provides a fundamental basis for the future development of proactive geoconservation policies in Portugal. Recent policy developments provide a favourable context for strengthening geoconservation in Portugal. The revised National Strategy for Nature Conservation and Biodiversity 2030, approved in 2026, explicitly recognises geodiversity and geological heritage within national nature conservation policy and includes specific provisions for geodiversity conservation. This strengthened policy framework creates new opportunities for integrating the NIGH into conservation, territorial planning, and environmental management, reinforcing its potential role as a national reference for evidence-based geoconservation.

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Declarations

Competing interests There are no Competing Interests.

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