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From Quaternary research to territorial governance: the case of the Viana do Castelo Littoral Aspiring Geopark (NW Portugal)

Da investigação do Quaternário à governança territorial: o caso do Aspirante Geoparque Litoral de Viana do Castelo (NO de Portugal)

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Abstract Geoscientific research can provide the foundation for integrating geoheritage conservation into territorial management, although the transition from scientific knowledge to effective geoconservation remains insufficiently documented. This work examines the development of the Viana do Castelo Littoral Aspiring Geopark (NW Portugal) between 2005 and 2025, focusing on the contribution of Quaternary research to statutory protection, science education and municipal governance. A retrospective documentary case study combines scientific publications, institutional and legal records, municipal monitoring data (2018-2023) and a secondary synthesis of a published survey of school leaders. Research on the Quaternary evolution of the Minho–Neiva coast and successive geoheritage inventories provided the foundation for the classification of 13 Local Natural Monuments in 2016 and 2018. Subsequent initiatives included educational programmes, scientific facilities, interpretive infrastructure and ecological restoration, while management was transferred directly to the municipality in 2024. Monitoring recorded 4,402 laboratory users and 5,823 participants in 214 field trips (2018-2023), together with 5,058 gateway visits (2021-2023) and 6,032 QR-code accesses (2022-2023), approximately 91% of which occurred at coastal monuments. A published survey indicated favourable perceptions of municipal educational support, although its results do not isolate the geopark's contribution. The case illustrates how Quaternary research can underpin a municipal geoconservation strategy and support the development of educational and territorial resources. However, uneven infrastructure use and the absence of systematic outcome assessments highlight the need for continued monitoring of conservation effectiveness, educational benefits and management sustainability.

Keywords: Quaternary geoheritage, Geoconservation, Geological heritage inventory, Local Natural Monuments, Science education, Municipal governance.

Resumo A investigação geocientífica pode constituir a base para integrar a conservação do património geológico na gestão territorial, embora a transição do conhecimento científico para medidas efetivas de geoconservação permaneça insuficientemente documentada. Este trabalho analisa o desenvolvimento do Aspirante Geoparque Litoral de Viana do Castelo (NO de Portugal), entre 2005 e 2025, centrando-se no contributo da investigação sobre o Quaternário para a proteção legal do património geológico, a educação em ciência e a governança municipal. Através de um estudo de caso documental retrospetivo, foram analisadas publicações científicas, documentação institucional e legal, dados municipais de monitorização (2018-2023) e resultados publicados de um inquérito às lideranças escolares. A investigação sobre a evolução quaternária do litoral Minho–Neiva e os sucessivos inventários do património geológico fundamentaram a classificação de 13 Monumentos Naturais Locais, em 2016 e 2018. Posteriormente, foram desenvolvidos programas educativos, infraestruturas científicas e interpretativas e iniciativas de recuperação ecológica, tendo a gestão passado diretamente para o município em 2024. A monitorização registou 4402 utilizadores dos laboratórios e 5823 participantes em 214 saídas de campo (2018-2023), bem como 5058 visitas às portas do geoparque (2021-2023) e 6032 acessos por códigos QR (2022-2023), aproximadamente 91% dos quais nos monumentos costeiros. Um inquérito publicado revelou perceções favoráveis relativamente ao apoio educativo municipal, embora não permita isolar o contributo específico do geoparque. O caso demonstra como a investigação sobre o Quaternário pode fundamentar uma estratégia municipal de geoconservação e apoiar o desenvolvimento de recursos educativos e territoriais. Contudo, a utilização desigual das infraestruturas e a ausência de avaliações sistemáticas dos resultados evidenciam a necessidade de monitorização continuada da eficácia da conservação, dos benefícios educativos e da sustentabilidade da gestão.

Palavras-chave: Património geológico quaternário, Geoconservação, Inventário do património geológico, Monumentos Naturais Locais, Educação em ciência, Governança municipal.

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1. Introduction

A UNESCO Global Geopark is a single, unified geographical area where sites and landscapes of international geological significance are managed under a holistic concept of protection, education and sustainable development. By integrating geoheritage conservation with scientific research, education and community engagement, geoparks provide opportunities to promote sustainable territorial development while strengthening public awareness of geological processes and Earth history (UNESCO, 2026). The scientific identification, assessment and protection of geological heritage constitute fundamental steps in this process, providing the knowledge base upon which conservation measures, educational initiatives and territorial interpretation strategies can be developed.

Although geoparks may encompass several administrative territories, their development can also be supported by governance structures operating at the municipal scale. Arouca UNESCO Global Geopark, whose territory coincides with a single Portuguese municipality, illustrates this approach (Rocha *et al.*, 2010). The Viana do Castelo Littoral Aspiring Geopark (NW Portugal) represents another municipal-scale initiative, developed progressively from geoscientific research on the Quaternary and geomorphological evolution of the Minho–Neiva coast. Over two decades, this scientific foundation supported the identification and legal protection of geological heritage and the subsequent development of educational programmes, research facilities, interpretive infrastructure and territorial management initiatives.

Understanding how scientific research is translated into effective geoconservation policies and integrated territorial initiatives is particularly relevant for assessing the development of aspiring geoparks. In this context, the experience of Viana do Castelo provides an opportunity to examine the successive stages through which geological knowledge, institutional cooperation and municipal intervention contributed to the establishment of a territorial strategy centred on geoheritage.

This study aims to analyse the development of the Viana do Castelo Littoral Aspiring Geopark between 2005 and 2025, focusing on the transition from geoscientific research and geoheritage inventory to an integrated municipal strategy for geoconservation, education and territorial development. Specifically, the study seeks to: (i) document how Quaternary research and successive geoheritage inventories supported the legal protection and interpretation of geological heritage; (ii) examine the institutional arrangements and initiatives established to integrate geoconservation with science education, research infrastructure and territorial management; and (iii) characterise the implementation and recorded use of the resulting infrastructure, identifying achievements, limitations and challenges associated with this municipal-scale approach.

The analysis is based on a retrospective documentary case study, combining scientific publications, institutional and legal records, municipal monitoring data for 2018-2023 and a secondary synthesis of a published survey of school leaders (Sousa-Pereira & Carvalhido, 2025). Building on previous accounts of local geoheritage designation (Carvalhido *et al.*, 2016) and public interpretation (Henriques & Pena dos Reis, 2021), this study provides an integrated perspective on the evolution of the project, highlighting the relationships between scientific knowledge, statutory protection, institutional development and the practical implementation of geoconservation and educational initiatives.

2. Study area and methods

2.1. Geographical and geological setting

The Viana do Castelo Littoral Aspiring Geopark encompasses the entire municipality of Viana do Castelo, covering approximately 320 km² and comprising 92,860 inhabitants (PORDATA, 2026). Located on the Atlantic coast of NW Portugal, the municipality extends along 22.1 km of coastline and borders the municipalities of Caminha, Ponte de Lima, Barcelos and Esposende (Fig. 1).

The territory comprises two main geomorphological units: the littoral platform, including the coastal zone and the alluvial plains, and the marginal relief, encompassing the slopes and summit surfaces (CARVALHIDO, 2012). These contrasting geomorphological settings provide the territorial framework for the diversity of geological features and processes represented in the aspiring geopark (Fig. 2).

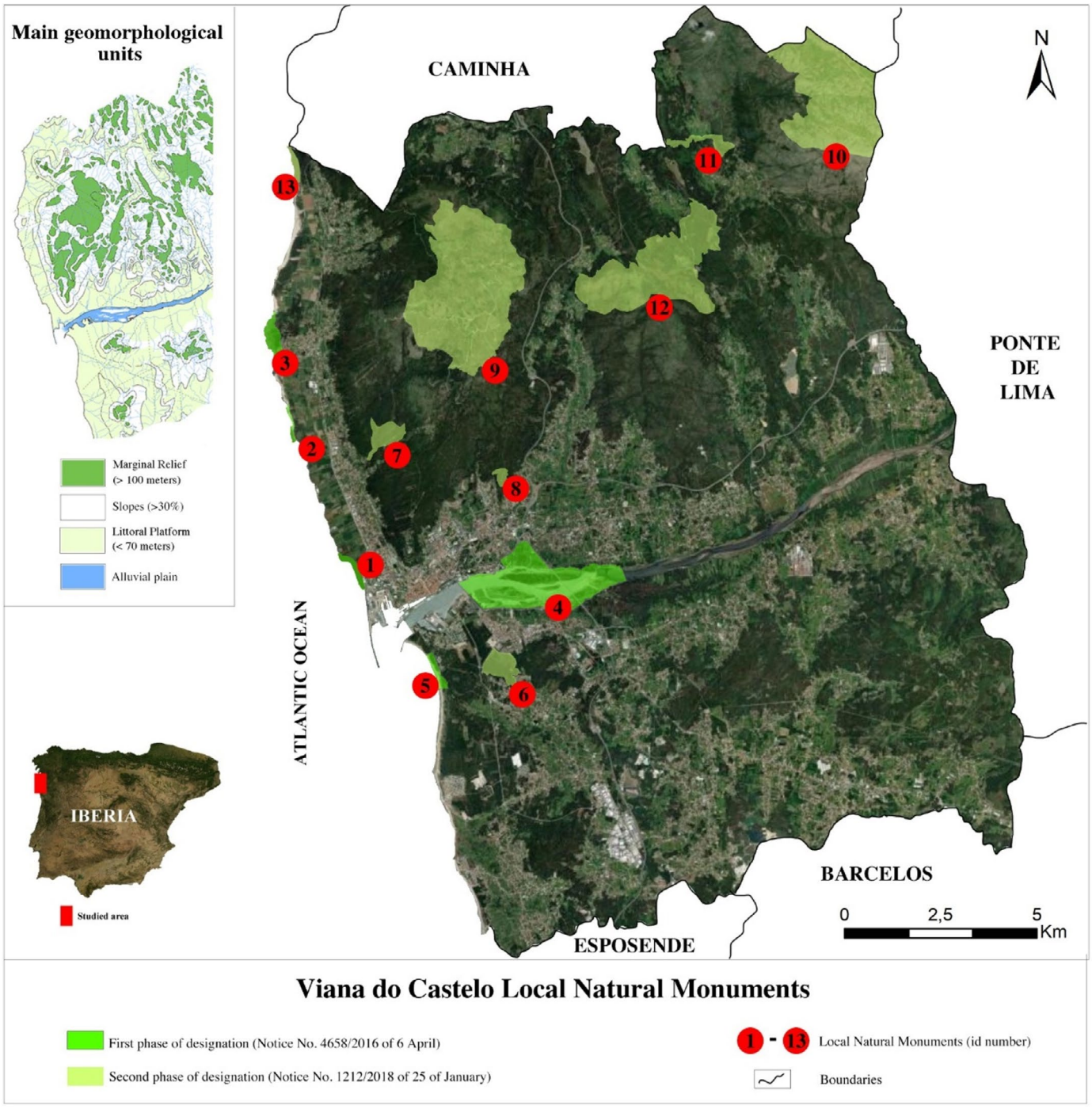


Fig. 1. Geographical distribution of the 13 Local Natural Monuments of Viana do Castelo (NW Portugal), distinguishing between the two phases of legal designation (2016 and 2018) and showing their setting within the two main geomorphological units (marginal relief and littoral platform). Map adapted from CARVALHIDO (2025). For the names of the Local Natural Monuments, refer to **Fig. 2**.

Fig. 1. Distribuição geográfica dos 13 Monumentos Naturais Locais de Viana do Castelo (NO de Portugal), distinguindo as duas fases de classificação legal (2016 e 2018) e o seu enquadramento nas duas principais unidades geomorfológicas (relevo marginal e plataforma litoral). Mapa adaptado de CARVALHIDO (2025). A designação dos Monumentos Naturais Locais é apresentada na **Fig. 2**.

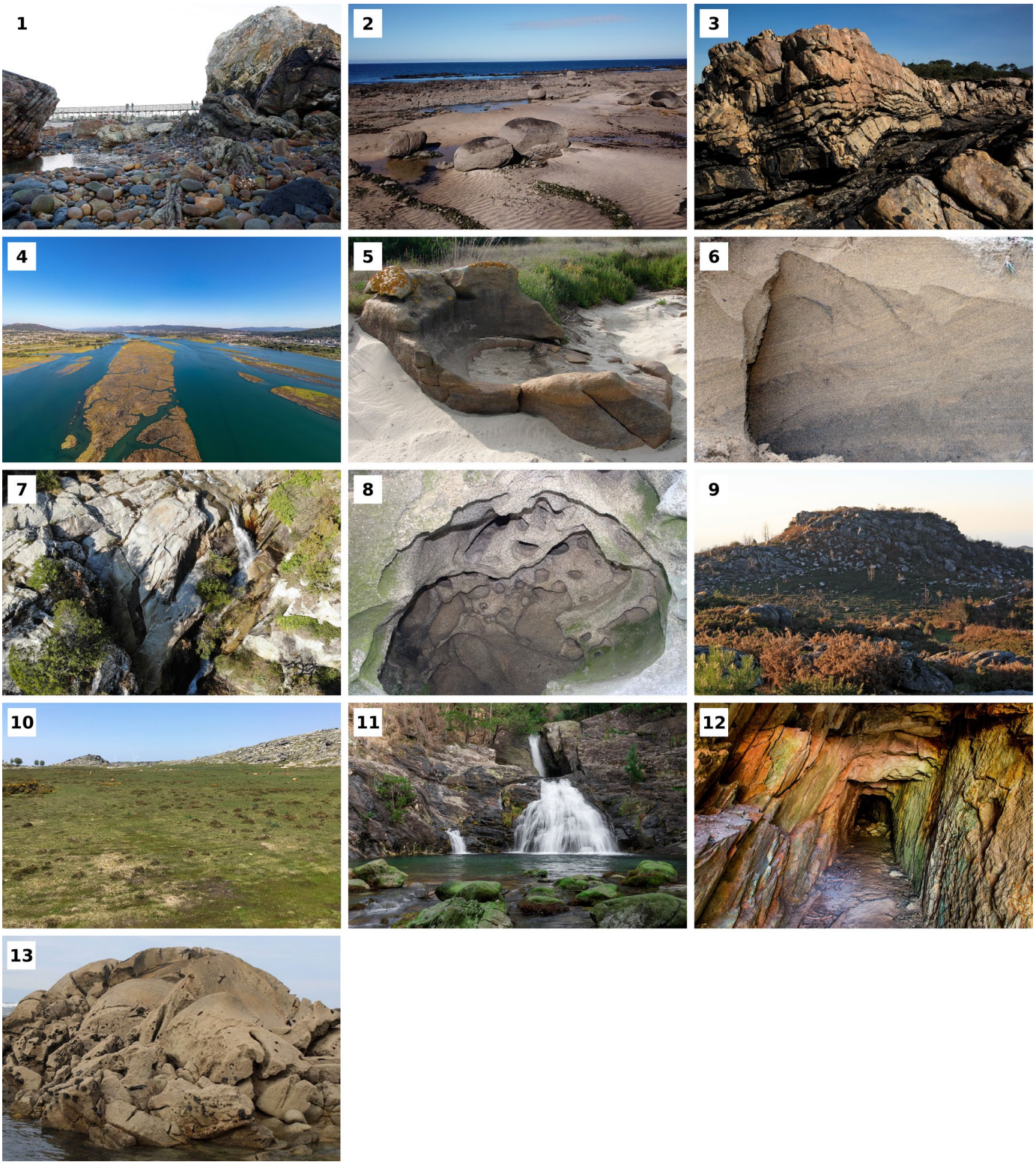


Fig. 2. Local Natural Monuments of Viana do Castelo: (1) Rheic Ocean Relics of Pedras Ruivas; (2) Magmatic Drops of Canto Marinho; (3) Ancient Beach Graveyard of the Montedor Coastal Cliff; (4) Ínsuas do Lima Fault; (5) Eemian Beach of Ribeira de Anha; (6) Climbing Dunes of Faro de Anha; (7) Poço Negro Waterfalls; (8) Penedo Furado of Monte da Meadela; (9) Granite Plateau of Chãs de Santa Luzia; (10) Peat Bogs of Chãs de Arga; (11) Ferida Má Waterfalls; (12) Quartzite Ridges of the Folgadoiro–Verdes Mining District; (13) Granite Pavements of Gatenha.

Fig. 2. Monumentos Naturais Locais de Viana do Castelo: (1) Relíquias do Rheic das Pedras Ruivas; (2) Gotas Magmáticas do Canto Marinho; (3) Cemitério das Praias Antigas do Alcantilado de Montedor; (4) Falha das Ínsuas do Lima; (5) Praia Eemiana da Ribeira de Anha; (6) Dunas Trepadoras do Faro de Anha; (7) Cascatas do Poço Negro; (8) Penedo Furado do Monte da Meadela; (9) Planalto Granítico das Chãs de Santa Luzia; (10) Turfeiras das Chãs de Arga; (11) Cascatas da Ferida Má; (12) Cristas Quartzíticas do Campo Mineiro de Folgadoiro–Verdes; (13) Pavimentos Graníticos da Gatenha.

The marginal relief corresponds to the Viana do Castelo–Caminha antiform, a Variscan structure mainly composed of successive two-mica granites, including the Bouça de Frade (syn-D2), Afife (syn-D3, ca. 313-319 Ma) and Arga (late-D3, ca. 306-311 Ma) granites (Simões, 1993; Dias *et al.*, 1998; Pamplona, 2001; Pamplona *et al.*, 2006). These granitoids are associated with Ordovician metasedimentary formations and tectonic units belonging to the Central Iberian and Galicia–Trás-os-Montes zones, which also host pegmatites and mineralisations exploited from Roman times to the twentieth century (Pereira, 1992; Lima, 2006; Alves, 2014; Meireles *et al.*, 2014).

The geomorphological evolution of the territory is expressed by a succession of planation surfaces, structural landforms and drainage adjustments. The Arga summit surface, at approximately 800 m altitude, is interpreted as a possible remnant of the fundamental surface of the Iberian Meseta, probably of Palaeogene age. Below this level, seven planation surfaces have been identified, ranging from the Santa Luzia Surface to the Darque Surface (0-20 m) (Carvalhido, 2012; Carvalhido & Pereira, 2015). Their distribution and deformation, together with evidence of stream capture and knickpoint development, reflect the influence of tectonic structures on landscape evolution, particularly north of the Lima River.

2.2. Quaternary record and geomorphological heritage

The Quaternary geological record constitutes a major component of the scientific heritage of the territory and provided the initial basis for the aspiring geopark project. Building on previous investigations along the Minho coast (Texier & Meireles, 1987; Meireles, 1992), research undertaken between 2005 and 2012 identified and characterised a succession of coastal platforms and sedimentary deposits recording relative sea-level changes, tectonic deformation and palaeoenvironmental evolution (Carvalhido, 2012).

The Quaternary record is particularly well represented on the Darque Surface, where six stepped coastal platforms were identified: platform I (18 m, MIS 11?), II (13 m, MIS 9?), III (7.3-9.3 m, MIS 7?), IV (4.5-5.5 m, MIS 5e), V (2-3.5 m, MIS 5e) and VI (up to 1.8 m, MIS 1). These platforms preserve geomorphological indicators of former shorelines, including marine notches, potholes and *Paracentrotus lividus* borings, which were used to reconstruct relative sea-level positions and investigate neotectonic activity.

Vertical deformation rates calculated for different periods range from -0.149 mm/yr (MIS 9-MIS 7) to +0.257 mm/yr (MIS 7-MIS 5e). Platform IV occurs approximately 1 m lower south of the Lima River, a difference interpreted as evidence of differential tectonic movement associated with the Lima fault, with an estimated mean uplift of approximately 8 mm/ka since MIS 5 (Carvalhido, 2012; Carvalhido *et al.*, 2014c).

The sedimentary record complements the geomorphological evidence and documents successive Quaternary environmental conditions. Sixteen lithostratigraphic units, chronologically constrained by radiocarbon and OSL dating and stratigraphic correlation, are interpreted to span the interval from MIS 9 to MIS 1, recording marine, fluvial, aeolian, lacustrine and periglacial environments (Carvalhido & Pereira, 2014; Carvalhido *et al.*, 2014b,c).

Among the most significant deposits are the Forte do Cão Conglomerates and Sands, associated with a high-energy Eemian beach; fluvial and aeolian deposits attributed to MIS 4-MIS 3; the Cambôa do Marinheiro Silts, containing charcoal dated to approximately 13 ka cal BP; and the Rego de Fontes Conglomerates and Sands, related to deglaciation processes.

Holocene and historical environmental changes are also represented in the territory. The Atlantic peat bogs of the Arga plateau preserve palaeoenvironmental records spanning approximately 8000-500 cal BP (Gómez-Orellana *et al.*, 2010), while the Ribeira da Areia Sands (OSL ages of 1590-1650) and Galeão Sands (1780-1800, Dalton Minimum) document fluvial and aeolian activity, respectively, during the Little Ice Age, including the development of climbing dunes that buried the former parish of S. João de Ester (Abreu, 1987; Carvalhido, 2012).

Together, these geological and geomorphological features provide a record of long-term landscape evolution and constitute the scientific foundation for the identification, interpretation and protection of geoheritage in Viana do Castelo. Within the 26 thematic categories of the Portuguese National Geosite Inventory (LNEG), the territory encompasses seven categories (Table 1), which were subsequently integrated into the interpretive narrative developed for the aspiring geopark (Carvalhido, 2016, 2018).

Table 1. Geological heritage and management characteristics of the 13 Local Natural Monuments of Viana do Castelo (NW Portugal), including geomorphological setting, year of legal classification, geological interests and land tenure. Compiled from Carvalhido (2012, 2025) and Pereira *et al.* (2019).

Tabela 1. Características do património geológico e da gestão dos 13 Monumentos Naturais Locais de Viana do Castelo (NO de Portugal), incluindo o enquadramento geomorfológico, o ano de classificação legal, os interesses geológicos e o regime de propriedade. Compilado de Carvalhido (2012, 2025) e Pereira *et al*. (2019).

Local Natural Monument	Geomorphological sector	Year of legal recognition	Geological heritage - National Inventory thematic categories	Main geological and geomorphological interests	Land tenure
Ancient Beach Graveyard of the Montedor Coastal Cliff	Littoral platform	2016	Coastal landforms; Variscan tectonics; pre-Mesozoic granitoids; neotectonics	Stepped Pleistocene coastal platforms and Quaternary aeolian, fluvial, lacustrine and periglacial deposits; Bouça de Frade thrust; historical salt pans and fish traps.	Maritime public domain; private
Rheic Ocean Relics of Pedras Ruivas	Littoral platform	2016	Variscan tectonics; coastal landforms; Ordovician record (CIZ)	Ordovician quartzites with trace fossils; Variscan deformation structures; Eemian marine platforms and MIS 2 lacustrine sediments.	Maritime public domain
Magmatic Drops of Canto Marinho	Littoral platform	2016	Variscan tectonics; coastal landforms	Magmatic structures and contact metamorphism; Eemian coastal platforms and late-Pleistocene lagoon deposits; historical salt pans and fish traps.	Maritime public domain
Eemian Beach of Ribeira de Anha	Littoral platform	2016	Coastal landforms	Eemian marine platforms and Forte do Cão beach conglomerate; evidence of differential coastal block movement; marine pothole.	Maritime public domain
Granite Pavements of Gatenha	Littoral platform	2018	Coastal landforms	Granite pavement weathering and boulder formation; pegmatites; MIS 5e Forte do Cão coastal deposits; pre-Roman pavements.	Maritime public domain
Ínsuas do Lima Fault	Littoral platform	2016	Coastal landforms; neotectonics	Structural control of the lower Lima estuary by faults; estuarine sedimentary bars; historical salt-working landscape.	Fluvial public domain; private
Poço Negro Waterfalls	Slopes	2018	Relief and drainage (Iberian Massif)	Waterfalls and knickpoints between geomorphological surfaces; fault-related tilting and stream capture; historical water-mill tracks.	Fluvial public domain; public and private
Ferida Má Waterfalls	Slopes	2018	Relief and drainage (Iberian Massif)	Waterfalls on contrasting lithological units; thrust and fault structures; quartz boudins.	Commons (Amonde); fluvial public domain
Penedo Furado of Monte da Meadela	Slopes	2018	Relief and drainage; Ordovician record (CIZ)	Large granite tafoni and honeycomb weathering; granite boulders and castle-kopje; Ordovician sedimentary structures.	Private
Quartzite Ridges of the Folgadoiro–Verdes Mining District	Slopes	2018	Variscan tectonics	Variscan tectonostratigraphic domains; historical Sn-W-Au mining landscape and associated mining structures.	Commons (Amonde)
Peat Bogs of Chãs de Arga	Summit surfaces	2018	Pleistocene glaciations; relief and drainage	Arga summit surface; periglacial depressions and Holocene Atlantic peat bogs; late-Variscan granite.	Commons (Montaria)
Granite Plateau of Chãs de Santa Luzia	Summit surfaces	2018	Pre-Mesozoic granitoids; relief and drainage	Granitic summit surface and facies contacts; inselbergs and tafoni; historical mineral-processing remains and rock carvings.	Commons (Outeiro, Areosa, Carreço, Afife)
Climbing Dunes of Faro de Anha	Summit surfaces	2018	Coastal landforms	Planation surfaces and Little Ice Age climbing dunes; historical burial of S. João de Ester.	Municipal

2.3. Materials and methods

This study adopts a retrospective documentary case-study approach to reconstruct and analyse the development of the Viana do Castelo Littoral Aspiring Geopark between 2005 and 2025. The analysis combines three complementary sources of information: (i) scientific, institutional and legal documentation; (ii) municipal monitoring records of infrastructure use; and (iii) previously published results from a survey of school leaders.

The documentary analysis provides the chronological and institutional framework of the study. The sources include scientific publications concerning the geological and geomorphological heritage of the territory, collaboration protocols, legal notices and regulations published in the *Diário da República*, municipal council minutes and mayoral orders. These documents were consulted directly and are also compiled in the municipal monograph by Carvalhido (2025).

The first author (RC) was directly involved in the development of the aspiring geopark, initially through doctoral research and geoheritage inventory (2005-2012), subsequently coordinating the classification processes of the Local Natural Monuments (2012-2014 and 2016-2017), and serving as scientific coordinator of the project since 2017. He was also responsible for preparing funding applications supporting the project's implementation between 2017 and 2021. This involvement provided direct access to institutional information but may also have influenced its interpretation.

The documentary information was organised chronologically to identify the main stages of the project and the relationships between scientific research, geoheritage inventory, statutory protection, institutional development, educational initiatives and territorial management. Special attention was given to the transition from geoscientific research to the establishment of legal protection mechanisms and the subsequent implementation of scientific, educational and interpretive infrastructure.

Municipal monitoring records cover the period 2018-2023 and were compiled by the geopark's technical coordinator in a report dated 11 April 2024. These records include the booking system of the School Science Network, visitor counts at gateways and observatories, field trips organised by the geopark team, the school transport pool, website and mobile application analytics, and recorded QR-code accesses to interpretive devices.

The monitoring data were analysed descriptively, considering annual values, totals, proportions and ratios where appropriate. Each dataset retains its original measurement unit, including users, visitors, field trips, participants, kilometres travelled, recorded accesses and page views. Because the monitoring periods and measurement procedures differ between services, the datasets were examined separately and were not aggregated into an overall estimate of individual users or visitors.

The educational dimension was complemented by a secondary synthesis of the results of an online questionnaire conducted in 2025 among top and middle leadership representatives of the municipality's school clusters (Sousa-Pereira & Carvalhido, 2025). The survey addressed perceptions of curricular autonomy and flexibility and the contribution of municipal support structures, including resources associated with the aspiring geopark. Only published descriptive results were considered, without reanalysis of individual responses.

The integration of these sources allows the reconstruction of the project's development and the characterisation of its implementation and recorded use. However, the documentary and descriptive nature of the study does not allow causal relationships to be established between the initiatives implemented and their educational, environmental or socioeconomic outcomes.

To minimise potential interpretive bias, the analysis distinguishes documented activities and institutional decisions from independently demonstrated outcomes.

3. Scientific foundations and geoconservation

3.1. Scientific research and geoheritage inventory (2005-2017)

The scientific foundations of the Viana do Castelo Littoral Aspiring Geopark were established through successive stages of geomorphological research and geoheritage inventory, beginning in 2005. The initial research was undertaken within a doctoral research project (Carvalhido, 2012) that combined four complementary approaches: (i) geomorphological mapping of the northern Portuguese coast, including structural lineaments and planation surfaces; (ii) inventory, sedimentological characterisation and absolute dating of Quaternary coastal deposits; (iii) differential GPS (DGPS) surveying of coastal platforms and *Paracentrotus lividus* borings as indicators of former sea levels; and (iv) inventory and assessment of geomorphological heritage, considering vulnerability, tourism potential and educational use through a weighted assessment procedure.

The initial inventory identified 18 geosites, most of which presented high educational potential, while seven also showed high tourism potential. The assessment supported the identification of intervention priorities according to site vulnerability and established relationships between individual geosites and curricular contents at different educational levels. These results provided an initial scientific and methodological framework for subsequent geoconservation and educational initiatives. Preliminary findings were disseminated locally from 2008 onwards (Carvalhido, 2008; Carvalhido *et al*., 2008, 2009, 2010).

An important step towards the institutional involvement of local authorities occurred in 2010, when the Municipality of Viana do Castelo and seven parish councils contributed to the financing of radiocarbon and optically stimulated luminescence (OSL) dating. This cooperation was formalised through protocols between the University of Minho, the municipality and the parish councils of Afife, Darque, Carreço, Monserrate, Areosa, Vila Praia de Âncora and Moledo. The municipal protocol, signed on 12 April 2010, already referred to the possibility of establishing a geopark.

This early collaboration is particularly relevant because it demonstrates that local institutional support for geoscientific research preceded the formal development of the geopark project. The participation of municipal and parish authorities in financing scientific investigations contributed to establishing a relationship between geological knowledge and territorial institutions, which subsequently supported the development of the geoconservation strategy.

The geoheritage inventory was developed in two successive phases. The first, conducted between 2005 and 2012, focused on the littoral platform and provided the scientific basis for the classification of five Local Natural Monuments in 2016. The second, undertaken between 2012 and 2017, concentrated mainly on the marginal relief, extending the inventory to geological and geomorphological features beyond the coastal zone. The scientific characterisation of eight additional sites supported their subsequent legal classification in 2018 (Carvalhido, 2018).

The inventory and classification process was presented to the scientific community as an example of geoconservation promoted by local administration (Carvalhido *et al.*, 2014a, 2016, 2017). Subsequent scientific studies further supported the interpretation and public communication of the geological heritage, particularly through the development of interpretive panels for the eight monuments classified in the second phase (Pereira *et al.*, 2019).

Overall, the successive inventories illustrate the transition from scientific identification and assessment of geological heritage to its incorporation into municipal conservation and territorial interpretation policies.

3.2. Legal protection and geoconservation strategy (2016-2025)

The scientific inventory provided the basis for the legal protection of geological heritage through the classification of Local Natural Monuments (*Monumentos Naturais Locais, MNL*). Under the Portuguese Legal Regime for Nature Conservation and Biodiversity (Decree-Law 142/2008 of 24 July, Articles 15 and 20, as amended by Decree-Law 242/2015), municipalities may classify protected areas of local scope.

Viana do Castelo implemented this legal instrument in two phases. The first, established by Notice (*Aviso*) 4658/2016, published in the *Diário da República* on 6 April 2016, classified five Local Natural Monuments associated with the littoral platform: Ancient Beach Graveyard of the Montedor Coastal Cliff, Rheic Ocean Relics of Pedras Ruivas, Magmatic Drops of Canto Marinho, Eemian Beach of Ribeira de Anha and Ínsuas do Lima Fault.

The second phase, established by Notice 1212/2018 of 25 January 2018, classified eight additional monuments: Granite Pavements of Gatenha, Poço Negro Waterfalls, Ferida Má Waterfalls, Penedo Furado of Monte da Meadela, Quartzite Ridges of the Folgadoiro–Verdes Mining District, Granite Plateau of Chãs de Santa Luzia, Peat Bogs of Chãs de Arga and Climbing Dunes of Faro de Anha (Fig. 1; Table 1).

Together, the thirteen monuments cover approximately 2,827 ha and represent geological and geomorphological features documenting different stages of the evolution of NW Iberia over approximately 570 million years. They include evidence of Variscan tectonics and magmatism, structural and granite landforms, mineral resources, Quaternary coastal evolution, neotectonic activity and palaeoenvironmental changes.

Quaternary heritage is particularly significant within this network, being represented in eight of the thirteen monuments (Table 1). The protected features include Pleistocene coastal platforms and associated sedimentary sequences, Eemian marine deposits, evidence of tectonically controlled coastal and estuarine evolution, Holocene peat bogs and historical aeolian deposits associated with the Little Ice Age. These features provide a scientific basis for interpreting long-term environmental changes and constitute important resources for geoscience education and public awareness of landscape evolution.

The classified areas partly overlap three Natura 2000 Special Areas of Conservation (SACs) – *Litoral Norte* (PTCON0017), *Rio Lima* (PTCON0020) and *Serra de Arga* (PTCON0039) – which together cover approximately 4,800 ha within the municipality, with the overlap between the Local Natural Monuments and the SACs determined at approximately 930 ha, calculated by intersection. This spatial relationship highlights the potential for integrating geological heritage protection with the conservation of habitats, species and landscapes.

The implementation of geoconservation measures also involves different land-tenure arrangements, including maritime and fluvial public domains, private and municipal land, and community-managed land (*baldios*). Four upland monuments are located on community land governed by Law 75/2017 and managed by parish councils or commons' management bodies. This diversity of ownership and management responsibilities represents an important consideration for the implementation and long-term maintenance of conservation measures, requiring cooperation between municipal authorities and local stakeholders.

Beyond their scientific significance, several monuments also preserve evidence of historical relationships between human communities and coastal environments. Examples include the 713 pre-Roman salt pans identified at *Canto Marinho* (Costa *et al.*, 2012), medieval stone fish-traps (*cambôas*) documented along the *Carreço* coast since the royal inquiries of 1258 (Magalhães & Baptista, 2006), and archaeological rock carvings (Bettencourt *et al.*, 2017). These features illustrate the connections between geological heritage, landscape evolution and cultural practices, contributing to an integrated interpretation of the territory.

The geoconservation strategy received national recognition through the Geoconservation Prize awarded by ProGEO-Portugal in 2016 and again in 2022. The latter distinction acknowledged the scientific foundations of the inventory, the legal protection measures implemented, and the strategies developed for geoheritage interpretation and valorisation.

The classification of the thirteen Local Natural Monuments therefore represents a major outcome of the initial geoscientific research and successive inventory phases. It established a legally protected network of geological heritage sites that subsequently supported the development of scientific, educational and interpretive initiatives within the aspiring geopark.

Dias (2025) also assessed the risk of degradation associated with natural and mixed hazards affecting the aspiring geopark's geological heritage, providing a basis for identifying threats and establishing conservation priorities. These findings are being used by the Municipality of Viana do Castelo to inform the preparation of management plans for all 13 Local Natural Monuments within the framework of the existing Management Regulation.

4. Development of the aspiring geopark

4.1. Institutional development and governance (2016-2025)

Following the scientific inventory and legal classification of geological heritage, the Viana do Castelo Littoral Aspiring Geopark progressively developed an institutional framework involving local authorities, educational institutions, research organisations and community stakeholders (Table 2). This process began with the Protocol for the Development of the Geopark, signed on 16 October 2016 by the Municipality of Viana do Castelo, the Earth Sciences Departments of the Universities of Minho and Coimbra, the School of Education of the Polytechnic Institute of Viana do Castelo (ESE-IPVC), the environmental organisation Quercus and the Marine and Environmental Sciences Centre (MARE).

On 4th September 2017, the Geoparque Litoral de Viana do Castelo Association was established as a private non-profit organisation. Its founding members included the seven public school clusters, two private schools and the 27 parish councils and unions of the municipality, while representatives of economic, cultural, social and educational organisations participated in its governing bodies. A scientific council comprising thirteen academics from IPVC and the Universities of Minho and Coimbra, together with an advisory council, was subsequently appointed.

This institutional structure extended the project beyond its initial geoscientific foundations, establishing mechanisms for cooperation between scientific institutions, local administration, schools and civil society. The project was also recognised as an observer member of the Portuguese Forum of UNESCO Geoparks and subsequently of the Portuguese Network of UNESCO Global Geoparks in 2022.

A major institutional change occurred in 2024, when the Association was dissolved and management of the aspiring geopark was transferred directly to the municipality. The new structure comprises a Specialised Technical Team, established in July 2024, with ten senior municipal technicians covering geology and education, tourism, nature conservation, biodiversity, design and communication, archaeology and climate change. The Municipal Council of the

Table 2. Main scientific, geoconservation, educational and institutional milestones in the development of the Viana do Castelo Littoral Aspiring Geopark (2005-2025). Sources: Carvalhido (2025) and the legal instruments cited in the text.

Tabela 2. Principais marcos científicos, de geoconservação, educativos e institucionais do desenvolvimento do Aspirante Geoparque Litoral de Viana do Castelo (2005-2025). Fontes: Carvalhido (2025) e diplomas legais citados no texto.

Year	Main milestone
2005	Start of doctoral research and the first geoheritage inventory phase (littoral platform).
2010	Research cooperation protocols with the municipality and parish councils, including co-funding of absolute dating.
2012	Completion of doctoral research and start of the second inventory phase (marginal relief).
2016	Legal classification of five Local Natural Monuments; institutional protocol for development of the aspiring geopark.
2017	Establishment of the Geoparque Litoral de Viana do Castelo Association and scientific council; launch of structured educational initiatives.
2018	Legal classification of eight additional Local Natural Monuments; inauguration of seven School Science Network laboratories.
2019	Creation of the municipal interpretation network; environmental monitoring and ecological restoration initiatives developed.
2020	Start of ecological rehabilitation works and agreements with companies and associations for maintenance of classified areas.
2021	Opening of the Geopark Gateways and scientific/educational facilities; eighth school laboratory; installation of 164 interpretive devices.
2022	Second ProGEO-Portugal Geoconservation Prize.
2023	Opening of the Arga International Observatory; protocol with IPVC for preparation of the UNESCO application dossier.
2024	Transition to direct municipal management; establishment of a specialised technical team and approval of the Municipal Council regulation.
2025	Publication of the Municipal Council regulation; continued preparation of the UNESCO application dossier.

Geopark, whose final regulation was published in May 2025 (Notice 11817/2025/2), provides an advisory framework involving institutional partners and municipal representatives (Fig. 3).

A collaboration protocol signed with the 27 parish councils and unions in November 2024 further defined responsibilities for territorial management. Under this arrangement, the municipality provides technical support, coordination and promotion, while the parishes contribute to heritage identification, community involvement, logistical support and conservation activities. The Scientific Council was progressively strengthened from 2017 and currently comprises 24 members with expertise in the fields of biology, geology, archaeology, education, tourism, economics, music, the arts, literature, wine and gastronomy, and ethnography.

The transition to municipal management therefore reorganised the institutional framework while retaining formal mechanisms for partner participation. However, the existence of these mechanisms does not, by itself, demonstrate their effectiveness or the continuity of stakeholders' influence on decision-making.

The aspiring geopark also became connected to wider municipal and intermunicipal governance initiatives, particularly those concerning community-managed land, environmental management and climate adaptation. These include the Municipal Council of Commons, established in 2023, and the Municipal Council for the Environment and Climate Action. At the intermunicipal scale, the project *Da Serra d'Arga à Foz do Âncora* (2017-2019) supported the proposal to establish the Serra de Arga Regional Protected Landscape and the subsequent creation of the Association of Municipalities of Serra de Arga in 2023.

These arrangements illustrate the progressive integration of geoheritage management into broader territorial governance structures, although their contribution to conservation and sustainable development outcomes remains to be evaluated. The thirteen Local Natural Monuments are also incorporated into the Municipal Master Plan (*Plano Diretor Municipal*, PDM), which is currently under revision, providing a link between statutory geoheritage protection and municipal territorial planning.

The preparation of an application for UNESCO Global Geopark status was formalised through a protocol between the municipality and IPVC in June 2023. A multidisciplinary promoter team comprising 28 academics from IPVC and the Universities of Minho and Coimbra began work in March 2024, organised around the different components of the application dossier. The application dossier remains under preparation, with no definitive submission date established. Additional scientific studies, including work aimed at assessing the geological significance of the Variscan heritage, are being developed to support the application.

4.2. Science education and territorial interpretation (2017-2025)

Science education became a central component of the aspiring geopark in 2017, with the development of initiatives designed to connect local geological heritage, scientific research and school curricula. The Teacher's Book, presented that year to the municipality's seven public school clusters and two private schools, introduced the geological history of the territory and thirteen educational proposals covering different school levels. The initiative involved 1,177 teachers and was complemented by a School

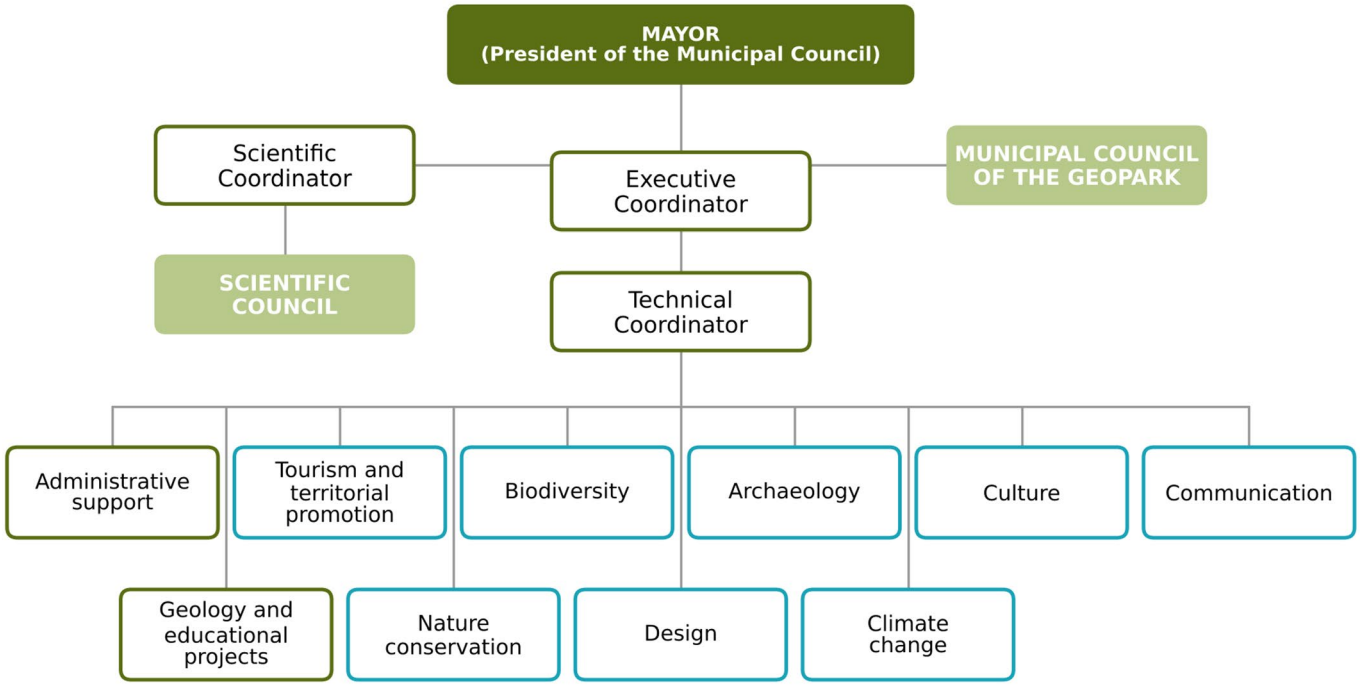


Fig. 3. Organisational structure of the Viana do Castelo Littoral Aspiring Geopark following the transition to direct municipal management in 2024. Adapted from Carvalhido (2025).
Fig. 3. Estrutura organizativa do Aspirante Geoparque Litoral de Viana do Castelo após a transição para a gestão municipal direta, em 2024. Adaptado de Carvalhido (2025).

Participatory Budget through which schools developed nineteen interdisciplinary projects, subsequently published in the *Livro de Projetos para a Flexibilização Curricular* (2018) (Fig. 4).

These initiatives provided the basis for the School Science Network (*Rede Escolar de Ciência e de Apoio à Investigação Científica*), inaugurated in January 2018. The network was initially organised around seven thematic laboratories installed in the municipality's public-school clusters, covering sedimentology, drilling and geophysics, science communication, petrology, microscopy and petrography, photogrammetry, and local memory. An eighth laboratory, dedicated to the propagation of native plant species for ecological restoration, was added in 2021.

The network was conceived as a decentralised scientific infrastructure linking laboratory activities with fieldwork at geological heritage sites. Scientific mentoring, specialised equipment and municipal transport support provided opportunities for students and teachers to participate in activities involving geological materials, scientific techniques and local environmental issues. The facilities were also made available to researchers conducting investigations in the territory.

The educational strategy was subsequently connected to national policies promoting curricular autonomy and flexibility, particularly Decree-Law 55/2018. A postgraduate programme in Education, Science and Local Heritage, established by ESE-IPVC in 2018, trained 28 teachers who formed seven Promoter Teams for Curricular Differentiation and Flexibility. These teams were supported by a Municipal Support Team created in 2019, which facilitated access to scientific infrastructure and territorial resources.

This arrangement sought to integrate local heritage into interdisciplinary educational projects and strengthen cooperation between schools, scientific institutions and municipal services. However, its implementation was disrupted by the COVID-19 pandemic in 2020. The subsequent perceptions of school leaders concerning municipal support and curricular flexibility are examined in Section 5.

From 2019 onwards, the educational and scientific infrastructure expanded beyond schools through three complementary networks: the Municipal Science Network, the Network of Geopark Gateways and the Municipal Network for the Interpretation of Natural and Cultural Heritage (Fig. 5; Table 3).

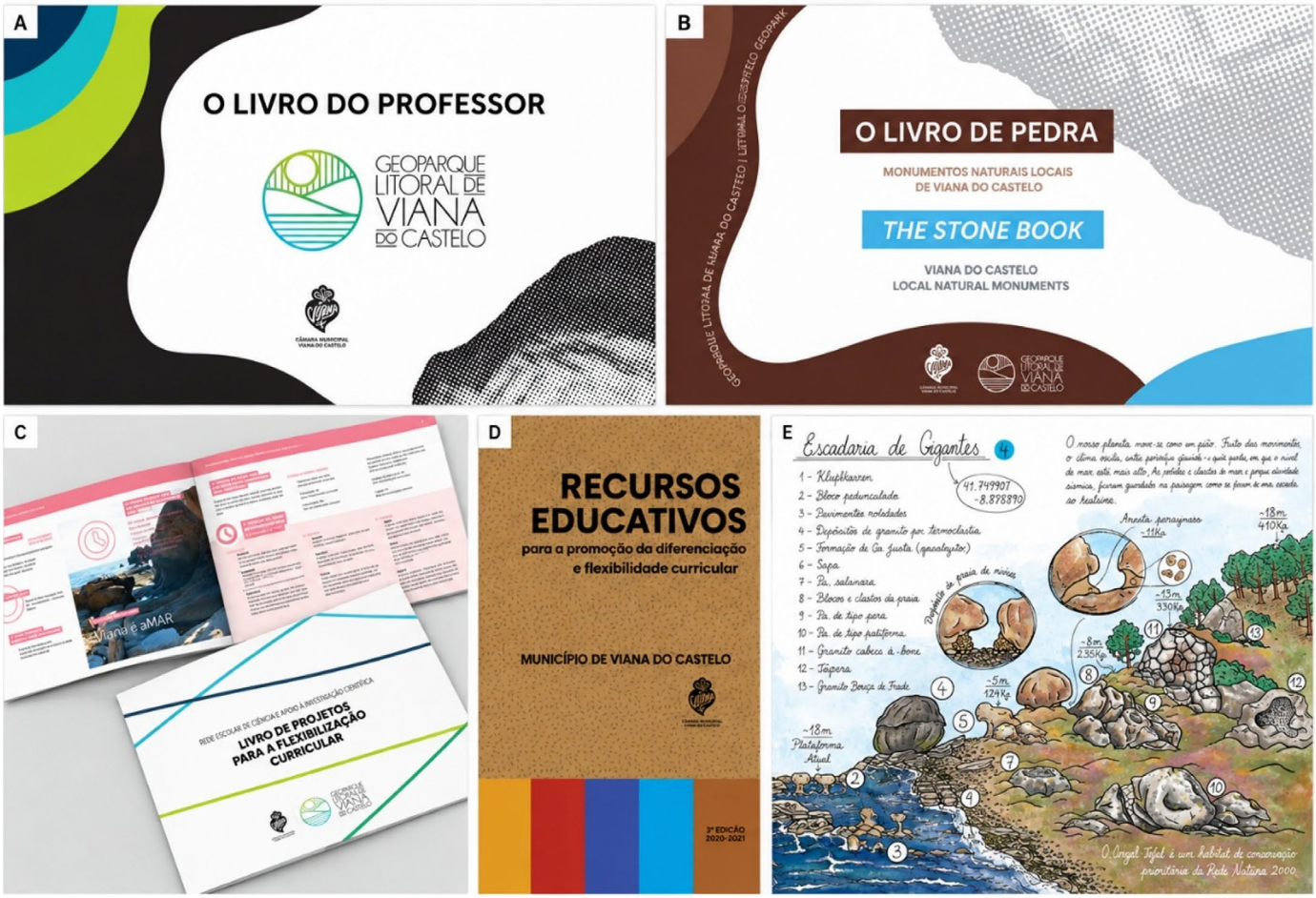


Fig. 4. Educational resources produced within the aspiring geopark: A) Teacher's Book (*O Livro do Professor*, 2017); B) The Stone Book (*O Livro de Pedra*), catalogue of the first five Local Natural Monuments (2016; 2nd edition 2018); C) Book of Projects for Curricular Flexibility (*Livro de Projetos para a Flexibilização Curricular*, 2018), published for the School Science Network; D) Educational Resources for the Promotion of Curricular Differentiation and Flexibility (3rd edition, 2020-2021); E) Feel the Heritage: Ancient Beach Graveyard of the Montedor Coastal Cliff (2021) – an illustration from the book – A Giants' Staircase (*Uma Escadaria de Gigantes*).

Fig. 4. Recursos educativos produzidos no âmbito do aspirante geoparque: A) O Livro do Professor (2017); B) O Livro de Pedra, catálogo dos cinco primeiros Monumentos Naturais Locais (2016; 2.ª edição 2018); C) Livro de Projetos para a Flexibilização Curricular (2018), publicado para a Rede Escolar de Ciência; D) Recursos Educativos para a promoção da diferenciação e flexibilidade curricular (3.ª edição, 2020-2021); E) Sentir o Património – Cemitério das Praias Antigas do Alcantilado de Montedor (2021) – exemplo de uma ilustração do livro – Uma Escadaria de Gigantes.

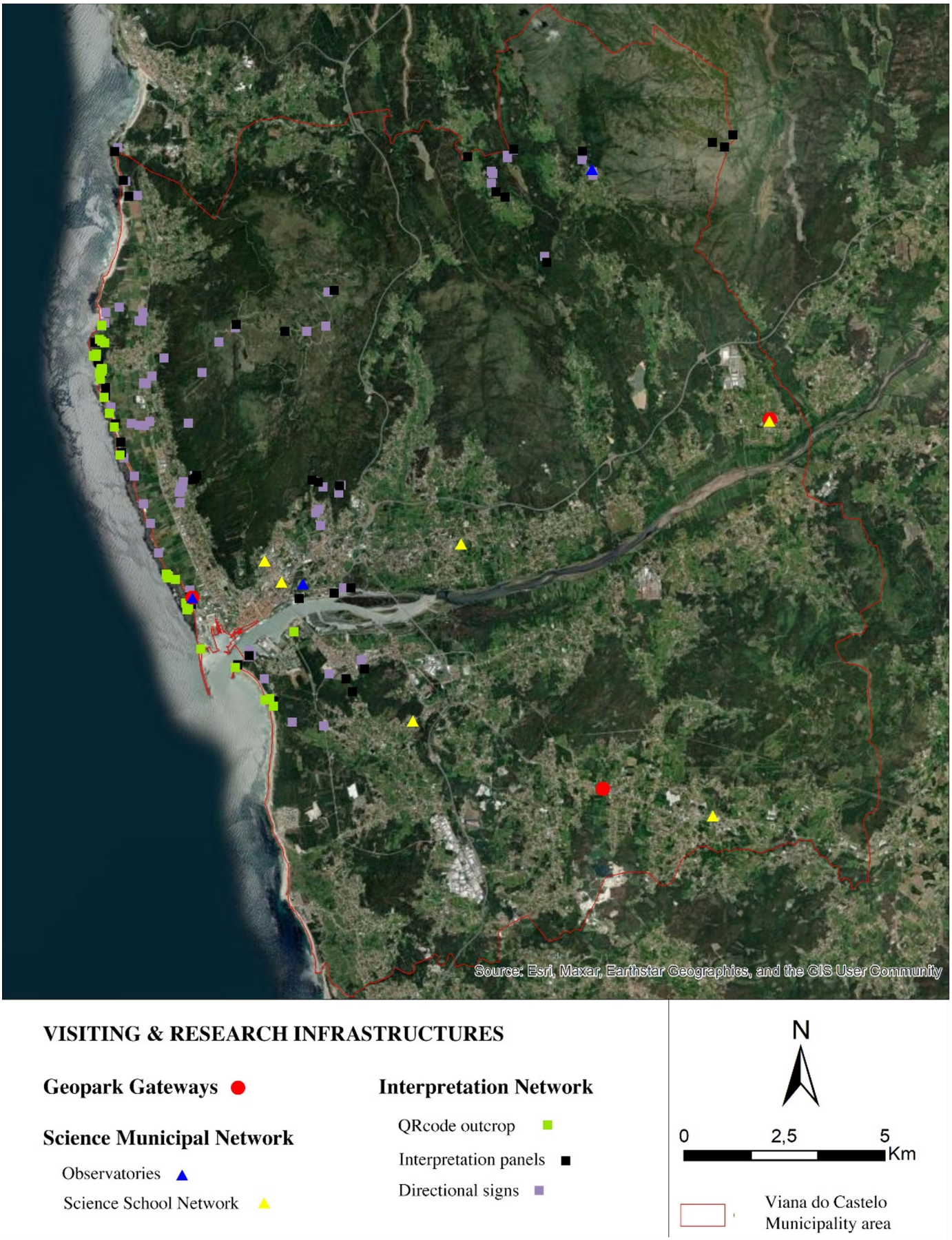


Fig. 5. Spatial distribution of the scientific, educational and interpretive infrastructure of the Viana do Castelo Littoral Aspiring Geopark, including the Geopark Gateways, scientific observatories, School Science Network laboratories and territorial interpretation facilities. Map reproduced from Carvalhido (2025).

Fig. 5. Distribuição espacial das infraestruturas científicas, educativas e interpretativas do Aspirante Geoparque Litoral de Viana do Castelo, incluindo as Portas do Geoparque, os observatórios científicos, os laboratórios da Rede Escolar de Ciência e os equipamentos de interpretação territorial. Mapa reproduzido de Carvalhido (2025).

The Municipal Science Network includes research and interpretation facilities, namely three observatories dedicated to the municipality's main geographical environments – the Atlantic coast, the Lima River and the mountain areas – and the School Science Network, a hub of eight laboratories at the head schools of seven public school clusters (Fig. 7). The Northern Coast Observatory, inaugurated in 2021, combines scientific facilities with spaces dedicated to marine literacy and palaeoenvironmental interpretation. The Urban Ecological Park, associated with the Lima River Observatory, provides a 20 ha tidal wetland environment for environmental interpretation and research. The Arga International Observatory, inaugurated in 2023, offers laboratory and accommodation facilities intended to support scientific activities in the mountain sector (Fig. 6).

The main goal of the School Science Network is to bring schools closer to scientific equipment, researchers and methods, and encourage teachers and students to approach the municipal territory as an integrated, interdisciplinary learning space through collaborative, project-based work, fostering the curricular autonomy and flexibility policy through curricular autonomy domains (Order 5908/2017 of 5 July and Decree-Law 55/2018 of 6 July).



Fig. 6. Municipal Science Network – Observatories: A) Arga International Observatory; B) Lima River Observatory/Urban Ecological Park; C) Northern Coast Observatory.
Fig. 6. Rede Municipal de Ciência – Observatórios: A) Observatório Internacional da Serra de Arga; B) Observatório do Rio Lima/Parque Ecológico Urbano; C) Observatório do Litoral Norte.



Fig. 7. School Science Network laboratories: A) Sedimentology Sample Processing Laboratory (Santa Maria Maior School Cluster); B) Photogrammetry Laboratory (Abelheira School Cluster); C) Laboratory of Memory (Lanheses School Cluster); D) Mechanical Drilling and Geophysics Laboratory (Monte da Ola School Cluster); E) Petrology Sample Processing Laboratory (Pintor José de Brito School Cluster); F) Microscopy and Petrography Laboratory (Barroselas School Cluster); G) Native Species Plant Propagation Laboratory (Santa Maria Maior School Cluster - Frei Bartolomeu dos Mártires School); H) Science Communication Laboratory (Monserrate School Cluster).

Fig. 7. Laboratórios da Rede Escolar de Ciência: A) Laboratório de Processamento de Amostras em Sedimentologia (Agrupamento de Escolas de Santa Maria Maior); B) Laboratório de Fotogrametria (Agrupamento de Escolas da Abelheira); C) Laboratório da Memória (Agrupamento de Escolas de Lanheses); D) Laboratório de Sondagem Mecânica e Geofísica (Agrupamento de Escolas do Monte da Ola); E) Laboratório de Processamento de Amostras em Petrologia (Agrupamento de Escolas do Pintor José de Brito); F) Laboratório de Microscopia e Petrografia (Agrupamento de Escolas de Barroselas); G) Laboratório de Propagação Vegetal de Espécies Autóctones (Agrupamento de Escolas de Santa Maria Maior - Escola Frei Bartolomeu dos Mártires); H) Laboratório de Comunicação de Ciência (Agrupamento de Escolas de Monserrate).

Table 3. Main scientific, educational and interpretive infrastructure developed within the Viana do Castelo Littoral Aspiring Geopark, including location, implementation period and principal functions. Source: Carvalhido (2025).

Tabela 3. Principais infraestruturas científicas, educativas e interpretativas desenvolvidas no âmbito do Aspirante Geoparque Litoral de Viana do Castelo, incluindo localização, período de implementação e principais funções. Fonte: Carvalhido (2025).

Infrastructure / network	Location	Opened / implemented	Principal functions
School Science Network (eight laboratories)	Head schools of seven public school clusters	2018; eighth laboratory in 2021	Laboratory-based science education, scientific mentoring, sedimentology, geophysics, petrography and native-plant propagation.
Northern Coast Observatory / Atlantic Gateway	Praia Norte	2021	Marine research and literacy; palaeoenvironmental interpretation; facilities for researchers and visitor itinerary planning.
Lima River Observatory / Urban Ecological Park	S. Vicente stream, Viana do Castelo	2021 (reopened)	Interpretation of tidal wetlands and halophyte habitats; environmental education and monitoring.
Arga International Observatory	S. Lourenço da Montaria	2023	Field research support; laboratory and accommodation facilities; Garrano horse, landscape and ecosystem studies.
Environmental monitoring and civil-protection network	Municipal territory (12 LoRaWAN antennas)	From 2019	Remote environmental and pedestrian-use monitoring; meteorological data and civil-protection applications.
Argas Gateway - Museum of Mining Heritage	Lanheses	2021	Reception and interpretation of upland landscapes, mining heritage and local history.
Neiva Gateway - Museum of Honey and Kaolin	Vila de Punhe	2021	Interpretation of palaeovegetation, kaolin, ceramics and beekeeping traditions.
Digital interpretation network	Online	2018-2021	Website, mobile app, virtual tour, BioRegisto platform and Virtual Museum of Maritime Memory.
On-site interpretation network	Classified Local Natural Monuments	2021	164 devices, including welcome panels, interpretive panels, outcrop-level QR codes and directional signs.

The Network of Geopark Gateways provides thematic access to the geological, biological and cultural heritage of different parts of the municipality. The Argas Gateway focuses on the mining heritage of the mountain areas, covering Local Natural Monuments nos. 9, 10, 11 and 12 (Fig. 1), while the Neiva Gateway interprets local geological resources, palaeovegetation and traditional activities. The Atlantic Gateway, integrated into the Northern Coast Observatory, provides information and tools for planning visits to the territory, and dedicated information on Local Natural Monuments no. 1 to 8 and 13 (Figs 1 and 8).

Territorial interpretation was further developed through physical and digital resources, including interpretive panels, thematic itineraries, a website and a mobile application launched in 2021 (Fig. 9). The Municipal Network for the Interpretation of Natural and Cultural Heritage incorporates georeferenced points of interest, virtual visits and digital tools designed to support formal and informal learning. A total of 164 interpretive devices were installed in 2021, extending access to information about geological, ecological and cultural features.

The project also developed digital and technological infrastructure, including a municipal LoRaWAN network intended to support environmental monitoring and visitor-management applications. Although this infrastructure provides opportunities for collecting data on environmental conditions and territorial use, the corresponding monitoring records were not available for analysis in the present study.

Together, these initiatives progressively transformed the legally protected geoheritage network into a broader territorial resource for scientific research, education and public interpretation. Their recorded use, including laboratory participation, field trips, gateway visits and interactions with digital interpretive resources, is examined in Section 5.

4.3. Geoconservation management and ecological restoration (2019-2025)

The implementation of the aspiring geopark also involved environmental management and ecological restoration initiatives, particularly within the classified Local Natural Monuments. These activities were developed in connection with wider municipal programmes for biodiversity conservation, forest recovery and climate adaptation.

In 2019, the municipality identified approximately 4,000 ha of Ecological Recovery Areas, encompassing burnt and classified areas, including Local Natural Monuments and Natura 2000 sites. The *Reforesting with Identity* programme, launched in the same year, promoted the planting of native tree species and community participation in forest recovery. Although these initiatives extended beyond geological heritage sites, they provided a broader environmental framework for the management of classified areas.

A more directly related intervention was the Programme for the Ecological Rehabilitation of the Classified Areas, submitted to POSEUR in 2019 and initiated in July 2020. With a reported investment of approximately €500,000, the programme targeted five Local Natural Monuments: Granite Pavements of Gatenha, Ancient Beach Graveyard of the Montedor Coastal Cliff, Eemian Beach of Ribeira de Anha, Ferida Má Waterfalls and Ínsuas do Lima Fault.



Fig. 8. Geopark Gateways: A) Neiva Gateway; B) Argas Gateway and C) Atlantic Gateway.
Fig. 8. Portas do Geoparque: A) Porta do Neiva; B) Porta das Argas e C) Porta do Atlântico.

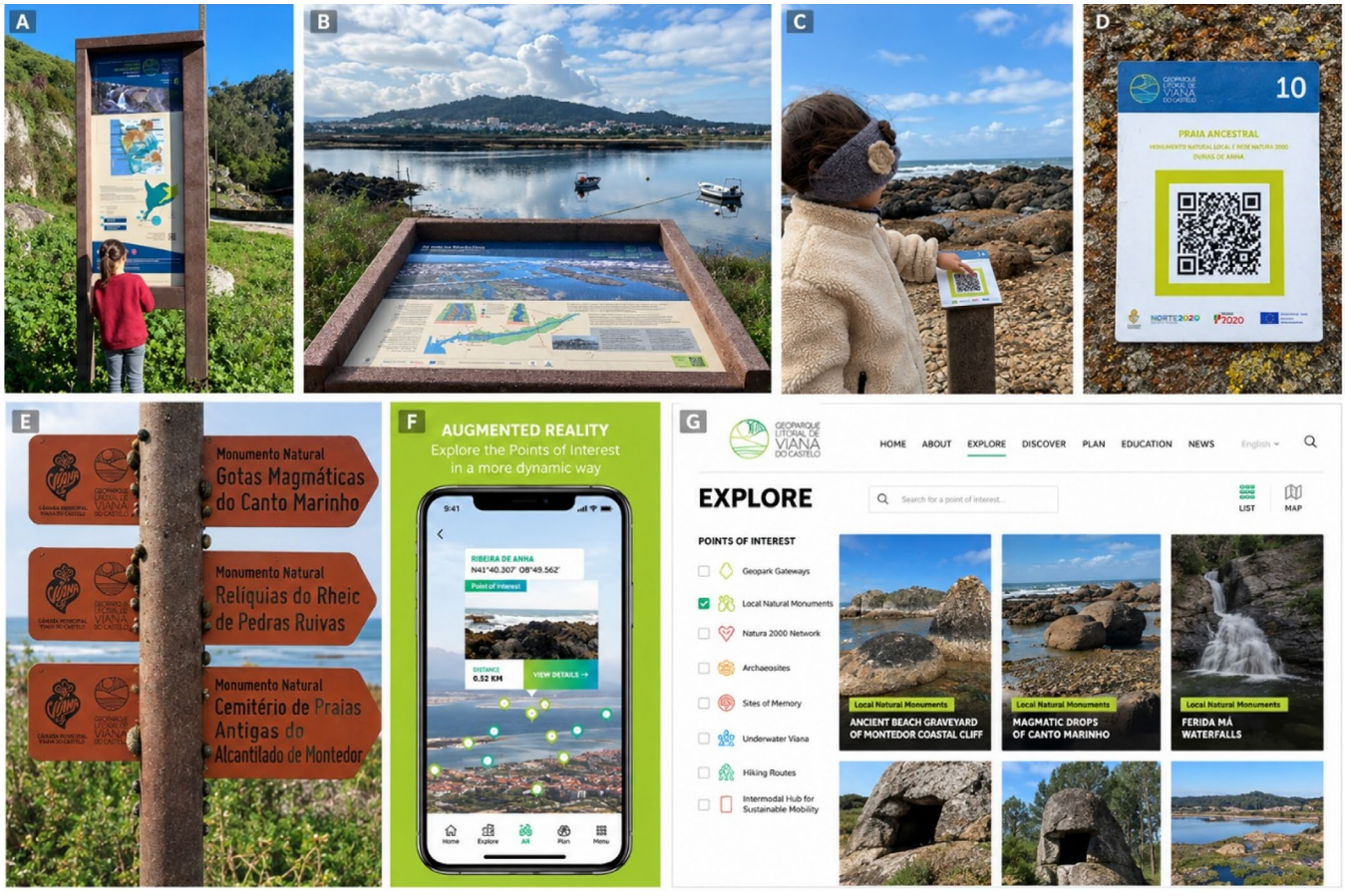


Fig. 9. Municipal Network for the Interpretation of the Natural and Cultural Heritage of Viana do Castelo: A) Welcome panels; B) Interpretive table; C) QR code for outcrop reading; D) Detail of a QR code installed on an outcrop; E) Directional arrows; F) Screen of the Geoparque Litoral Viana app, highlighting the augmented-reality feature available; G) General view of the "Explore" tab of the geopark website (www.geoparquelitoralviana.pt).

Fig. 9. Rede Municipal para a Interpretação do Património Natural e Cultural de Viana do Castelo: A) Painéis de acolhimento; B) Mesa interpretativa; C) Código QR para leitura de afloramento; D) Pormenor de código QR instalado em afloramento; E) Flechas direcionais; F) Aspeto do ecrã da app Geoparque Litoral Viana, destacando a tecnologia de realidade aumentada disponível; G) Aspeto geral do separador Explorar no sítio da internet do geoparque (www.geoparquelitoralviana.pt).

The interventions focused particularly on controlling invasive plant species, including *Acacia spp., Carpobrotus edulis, Arundo donax, Tradescantia fluminensis* and *Cortaderia selloana*. A five-year monitoring and maintenance plan involved parish councils, community organisations and commons' management bodies. Biological control of *Acacia longifolia*, using *Trichilogaster acaciae-longifoliae*, was also introduced locally in 2021 following consultation with conservation authorities and scientific specialists.

The long-term maintenance of restored areas emerged as an important management challenge, particularly because ecological interventions require continued monitoring and repeated control of invasive species. To involve local stakeholders, the municipality established cooperation agreements in July 2020 with eighteen companies and three associations, which committed to periodic maintenance activities in classified areas.

These maintenance arrangements remain active, complemented by municipal initiatives to control invasive vegetation and propagate native plant species through the School Science Network. However, restrictions on obtaining additional funding for repeated interventions in previously funded areas mean that subsequent maintenance activities must rely primarily on municipal resources, creating challenges for their long-term continuity.

Municipal records for 2019-2023 document 24 maintenance actions involving 384 participants. However, these activities were concentrated in four monuments: Ancient Beach Graveyard of the Montedor Coastal Cliff, Eemian Beach of Ribeira de Anha, Ferida Má Waterfalls and Ínsuas do Lima Fault. This uneven distribution indicates that the implementation of maintenance commitments varied between sites, highlighting the importance of sustained coordination and monitoring.

Other municipal environmental initiatives complemented these interventions, including programmes involving community-managed land, carbon sequestration (*Viana do Castelo Commons Carbon Bank*) and the identification of trees of municipal interest (*Trees of Memory* programme). The project was also connected to environmental management actions along the lower Lima estuary, where bank instability and invasive vegetation prompted interventions involving public authorities and private landowners.

The implementation of these initiatives required the mobilisation of financial resources from municipal, national and European programmes, together with contributions from institutional and community partners. The project record identifies approximately €1.9 million in six operations with specified amounts, including ecological rehabilitation, scientific infrastructure and an intermunicipal project. However, this subtotal combines different types of expenditure, including an intermunicipal operation whose share attributable to Viana do Castelo could not be determined. It therefore does not represent the total investment in the aspiring geopark, or the amount of external funding received.

The documented experience illustrates the importance of combining scientific knowledge, statutory protection, financial resources and stakeholder participation in the implementation of geoconservation measures. Nevertheless, the available records primarily document interventions and management arrangements, rather than their long-term effects on the conservation status of geological heritage sites.

5. Monitoring of infrastructure use

5.1. Recorded use of scientific and interpretive infrastructure (2018-2023)

Municipal monitoring records provide quantitative information on the use of the scientific, educational and interpretive infrastructure developed within the aspiring geopark. The available datasets cover different periods between 2018 and 2023, depending on the establishment of each facility and the availability of monitoring records (Fig. 10; Table 4). The results are presented separately for each service, as the indicators represent different types of use and cannot be combined into an overall number of individual visitors.

The School Science Network laboratories recorded 4,402 users between 2018 and 2023, with substantial annual variation. The number increased from 386 in 2018 to 1,161 in 2019, before declining to 484 in 2020 and 114 in 2021, during the COVID-19 pandemic. Activity subsequently recovered, reaching 1,022 users in 2022 and 1,235 in 2023, exceeding the pre-pandemic maximum.

Laboratory use was unevenly distributed among the different facilities. The sedimentology laboratory recorded 1,458 users, approximately one-third of the total, followed by microscopy and petrography (602) and petrology (380). The Laboratory of Memory recorded no bookings, while three laboratories had no recorded users after 2020.

The native-species propagation laboratory, established in 2021, became particularly important in the post-pandemic period, recording 610 users in 2022 and 815 in 2023. These values represented approximately 60% and 66% of the respective annual totals, indicating a concentration of recorded laboratory use in activities associated with ecological restoration.

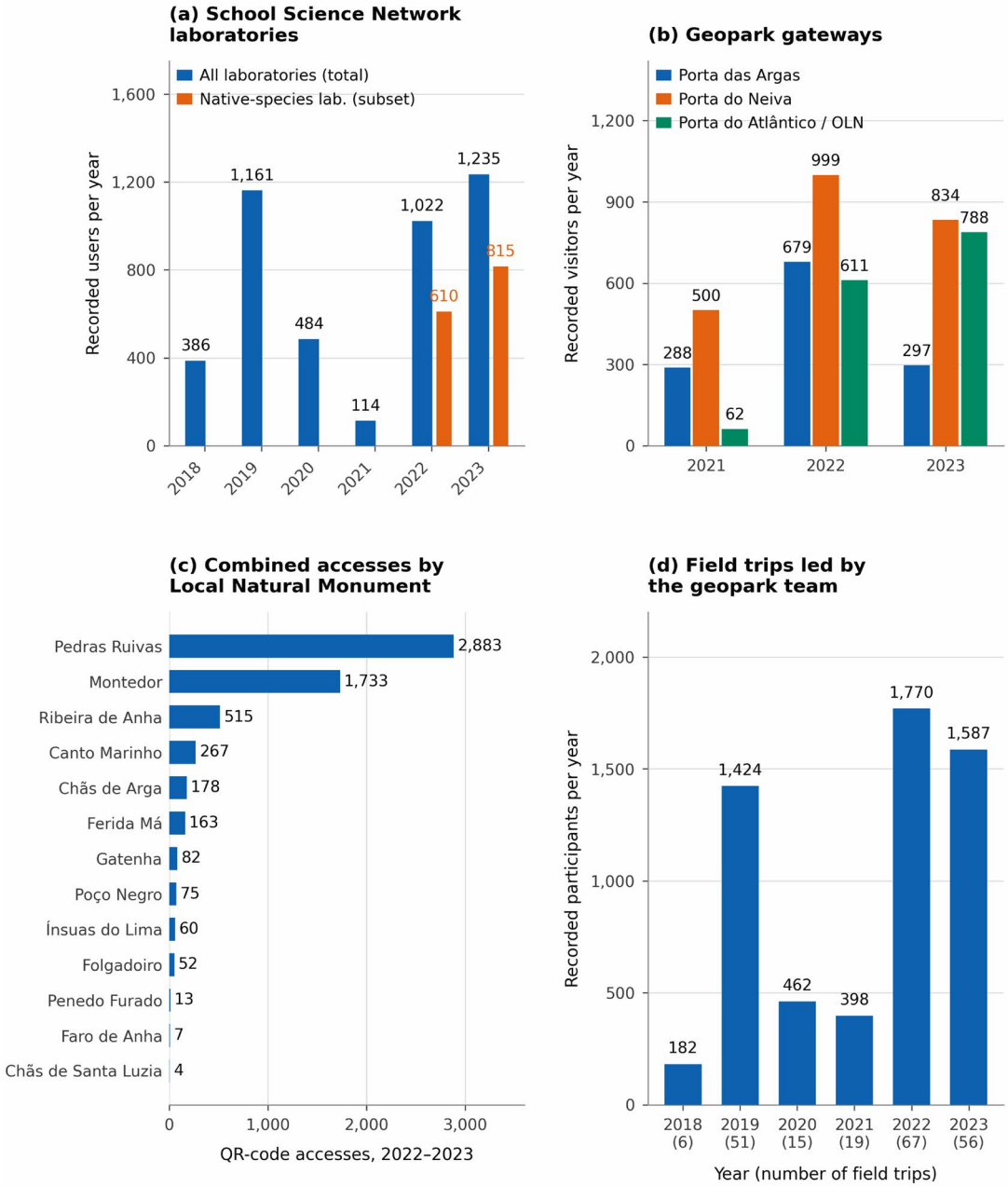


Fig. 10. Recorded use of scientific, educational and interpretive resources of the Viana do Castelo Littoral Aspiring Geopark (2018-2023): (a) Annual users of the School Science Network laboratories, highlighting the contribution of the native-species propagation laboratory in 2022-2023; (b) Annual visitors to the Geopark Gateways, with the Atlantic Gateway and Northern Coast Observatory (OLN) sharing the same visitor records; (c) QR-code accesses to interpretive panels and outcrop-level plaques at the 13 Local Natural Monuments (2022-2023); and (d) Annual field-trip participants and number of field trips (in parentheses). Source: municipal monitoring records (Municipality of Viana do Castelo).

Fig. 10. Utilização registada dos recursos científicos, educativos e interpretativos do Aspirante Geoparque Litoral de Viana do Castelo (2018-2023): (a) Utilizadores anuais dos laboratórios da Rede Escolar de Ciência, destacando o contributo do laboratório de propagação de espécies nativas em 2022-2023; (b) Visitantes anuais das Portas do Geoparque, sendo os registos da Porta do Atlântico e do Observatório do Litoral Norte (OLN) comuns às duas infraestruturas; (c) Acessos por códigos QR aos painéis interpretativos e às placas junto dos afloramentos nos 13 Monumentos Naturais Locais (2022-2023); e (d) Participantes anuais nas saídas de campo e respetivo número de saídas (entre parênteses). Fonte: registos de monitorização municipal (Município de Viana do Castelo).

Table 4. Annual records of scientific, educational and interpretive infrastructure use in the Viana do Castelo Littoral Aspiring Geopark (2018-2023), by facility and monitoring indicator. Source: municipal monitoring records (Municipality of Viana do Castelo).

Tabela 4. Registos anuais de utilização das infraestruturas científicas, educativas e interpretativas do Aspirante Geoparque Litoral de Viana do Castelo (2018-2023), por equipamento e indicador de monitorização. Fonte: registos de monitorização municipal (Município de Viana do Castelo).

Service / indicator	2018	2019	2020	2021	2022	2023	Total
School Science Network laboratories - users	386	1161	484	114	1022	1235	4402
Of which native-species propagation laboratory - users	-	-	-	-	610	815	1425
Field trips led by geopark team - trips	6	51	15	19	67	56	214
Field trips led by geopark team - participants	182	1424	462	398	1770	1587	5823
School transport booked via network website - km	210	4500	930	4158	1922	4851	16571
Northern Coast Observatory / Atlantic Gateway - shared visitors	-	-	-	62	611	788	1461
Arga International Observatory - visitors	-	-	-	-	-	10	10
Urban Ecological Park - visitors	293*	closed	closed	46421	55763	78227	180704
Argas Gateway - visitors	-	-	-	288	679	297	1264
Of which organised groups - visitors	-	-	-	255	469	168	892
Neiva Gateway - visitors	-	-	-	500	999	834	2333
Of which organised groups - visitors	-	-	-	232	836	666	1734
Interpretive panels (13 monuments) - QR-code accesses	-	-	-	-	373	2060	2433
Outcrop-level plaques (5 monuments) - QR-code accesses	-	-	-	-	448	3151	3599
Geopark website - recorded users	-	-	-	6513	14332	18266	39111
Geopark website - page views	-	-	-	32653	55058	60011	147722
Mobile app - recorded users	-	-	-	914	216	226	1356
Mobile app - views	-	-	-	27127	2418	2427	31972

* Records for 2018 refer to the period preceding the temporary closure of the Urban Ecological Park, which reopened in June 2021.

Field trips organised by the geopark's scientific and technical team included visits to Local Natural Monuments, Natura 2000 sites, archaeological sites and other heritage locations. Between 2018 and 2023, 214 field trips were recorded, involving 5,823 participant records, corresponding to an average of approximately 27 participants per trip. Activity declined during the pandemic and reached its maximum in 2022, with 67 trips and 1,770 participants. The municipal school transport service associated with the network recorded 16,571 km over the same period.

Visitor records from the scientific observatories reveal substantial differences between facilities. The Urban Ecological Park recorded 180,411 visits between its reopening in June 2021 and December 2023, with annual counts increasing from 46,421 in 2021 to 78,227 in 2023. Including 293 visits recorded in 2018, before its closure, the total reported is 180,704.

The Northern Coast Observatory recorded 1,461 visitors between 2021 and 2023, while the Arga International Observatory registered ten visitors in its opening year (2023). These figures reflect different patterns of recorded use, although the facilities also differ in their functions, accessibility and periods of operation.

The three Geopark Gateways recorded 5,058 visits between 2021 and 2023, comprising 1,264 at the Argas Gateway, 2,333 at the Neiva Gateway and 1,461 at the Atlantic Gateway. The latter shares its visitor count with the Northern Coast Observatory, as both correspond to the same facility. Consequently, these records should not be interpreted as independent visitor totals when comparing the different infrastructure networks.

Digital interpretation resources also generated measurable interactions with geological heritage sites. Between 2022 and 2023, the QR codes installed at the thirteen Local Natural Monuments recorded 6,032 accesses, comprising 2,433 accesses to interpretive panels and 3,599 to outcrop-level plaques.

Approximately 91% of these accesses were concentrated in the five coastal monuments, indicating a marked spatial concentration of recorded digital interactions. At these sites, outcrop-level plaques generated more accesses than interpretive panels (3,599 and 1,859, respectively). These differences reflect recorded interactions with distinct interpretive devices and should not be interpreted as direct indicators of visitor preferences.

This spatial concentration partly reflects the interpretive strategy adopted for the coastal monuments, where the diversity of geological features exposed in intertidal outcrops justified the installation of 40 QR codes directly on geological surfaces. In most inland monuments, interpretation relies primarily on landscape interpretation panels, and the differences in device distribution should therefore be considered when comparing recorded digital interactions.

The geopark website recorded an increase from 6,513 users in 2021 to 18,266 in 2023, approximately a 2.8-fold increase. The annual figures totalled 39,111 recorded users and 147,722 page views over the three-year period. In contrast, the mobile application registered 914 users in 2021, followed by 216 in 2022 and 226 in 2023.

These contrasting trajectories indicate differences in the recorded use of digital communication channels. However, website and application analytics are based on distinct measurement procedures and should not be interpreted as directly comparable indicators of individual engagement.

Overall, the monitoring records document the use of the infrastructure developed within the aspiring geopark, while revealing substantial variation between facilities, services and periods. The results also highlight the importance of maintaining consistent monitoring procedures to support future assessments of educational participation, public engagement and territorial interpretation.

5.2. School leaders' perceptions of educational support (2025)

The educational dimension of the aspiring geopark was further contextualised through a secondary synthesis of a previously published study examining school leaders' perceptions of curricular autonomy, flexibility and municipal support (Sousa-Pereira & Carvalhido, 2025).

The online questionnaire, conducted at the end of the 2024/2025 school year, received 23 responses from 58 potential participants (40%), including school directors, department coordinators and coordinators of curricular autonomy domains (*Domínios de Autonomia Curricular, DAC*).

The results indicate generally favourable perceptions of municipal support for educational activities involving local territorial resources. Approximately 80% of respondents associated the national curricular flexibility policy with greater recognition of the local component of the curriculum, including interdisciplinary projects involving natural and cultural heritage.

Regarding municipal support conditions, 74% considered the available infrastructure, resources and services important or decisive for implementing curricular flexibility. These resources included the aspiring geopark, the *Ciência Viva* school clubs and the Centre for Environmental Monitoring and Interpretation. Furthermore, 70% rated cooperation with the Municipal Support Team as effective or very effective.

However, perceptions of the Promoter Teams for Curricular Differentiation and Flexibility were less favourable. While 43% of respondents considered their contribution to school dynamics moderate or very significant, 56% reported a reduced or null impact. The main difficulties identified concerned organisational constraints, including timetables, class sizes, available spaces and resources, as well as the continuity of support and the interruption caused by the COVID-19 pandemic.

These findings suggest that municipal resources were generally valued by the participating school leaders, while the institutional integration and continuity of educational initiatives remained challenging. Nevertheless, the results must be interpreted cautiously. The study addressed a broader set of municipal educational policies and support mechanisms, of which the aspiring geopark was only one component.

Consequently, the survey does not provide an independent assessment of the geopark's educational impact, nor does it establish effects on student learning. The relatively small number of respondents, unequal participation across leadership roles and absence of school-level identification further limit the generalisation and comparison of the findings.

6. Discussion

The development of the Viana do Castelo Littoral Aspiring Geopark illustrates how geoscientific research can provide the foundation for a progressively broader strategy of geoheritage conservation, education and territorial management. Over two decades, scientific investigations and successive inventories were followed by statutory protection, institutional development and the establishment of educational, scientific and interpretive infrastructure. Rather than representing independent initiatives, these developments reveal a progressive integration of geological knowledge into municipal policies and territorial resources. However, the documented sequence does not, by itself, demonstrate causal relationships between individual interventions and their outcomes.

6.1. From Quaternary research to statutory geoconservation

One of the most distinctive features of the Viana do Castelo experience is the central role of Quaternary research in the development of a municipal geoconservation strategy. The geomorphological and sedimentological investigations undertaken along the Minho–Neiva coast provided the scientific basis for identifying and assessing geological heritage, particularly the coastal platforms, sedimentary sequences and palaeoenvironmental records documenting Quaternary landscape evolution.

The subsequent classification of thirteen Local Natural Monuments demonstrates how scientific inventories can support the application of statutory protection instruments at the municipal scale. The Portuguese legal framework established by Decree-Law 142/2008 enabled the local administration to classify geological heritage sites in two successive phases, extending protection from the littoral platform to the marginal relief (Carvalhido *et al.*, 2016). This process illustrates the importance of combining

scientific knowledge with institutional commitment to implement geoconservation measures.

The early involvement of the municipality and parish councils in financing radiocarbon and OSL dating is particularly relevant in this context. Their participation preceded the formal establishment of the geopark and contributed to strengthening cooperation between research institutions and local authorities. This experience suggests that institutional engagement during the scientific investigation stage may facilitate the subsequent incorporation of geological heritage into territorial policies, although the available documentation does not establish the extent of this contribution.

The Quaternary record also provided a coherent interpretive framework linking geological processes, environmental changes and human occupation. Eight of the thirteen Local Natural Monuments preserve Pleistocene or Holocene features, while the gateways and interpretive infrastructure address sea-level changes, climatic oscillations and their relationships with coastal landscapes and historical activities. Examples include Eemian marine deposits, Holocene palaeoenvironmental records and Little Ice Age aeolian formations, together with archaeological evidence of coastal resource use.

This integration of geological and cultural information is particularly relevant for communicating the significance of Quaternary heritage beyond the scientific community. The chronological framework established through absolute dating (Carvalhido *et al.*, 2014c) provides a basis for interpreting environmental changes at different timescales and relating them to present-day landscapes.

The monitoring records indicate that approximately 91% of QR-code accesses in 2022-2023 were associated with the five coastal monuments, with Pedras Ruivas and Montedor accounting for 76.5% of the recorded accesses (Fig. 10c). This concentration suggests that coastal geoheritage constitutes an important focus of recorded digital interaction within the interpretive network. However, differences in accessibility, visitor numbers, device distribution and interpretive content may influence these patterns, and the available data do not allow their respective contributions to be determined.

The continued use of the territory for scientific research further reinforces the relationship between geoheritage conservation and knowledge production. Master's research addressing monument interpretation (Melo, 2019), mining heritage (Mata, 2020; Fernandes, 2022), invasive species management (Costa, 2019), Little Ice Age heritage (Caramez, 2021) and geodiversity along pedestrian trails (Neves, 2021) illustrates the diversity of subsequent research activities associated with the territory.

Nevertheless, statutory protection should not be equated with demonstrated conservation effectiveness. Although the classification of the monuments established a legal framework for their protection, evaluating the long-term outcomes of geoconservation measures would require systematic information on site conditions, degradation pressures, management interventions and their effectiveness. The distinction between legal designation and conservation outcomes is therefore essential when interpreting the achievements of the project.

6.2. Geoheritage as a resource for education and territorial development

A second important dimension of the Viana do Castelo experience is the integration of geological heritage into science education and territorial interpretation. The establishment of the School Science Network, followed by the development of observatories, gateways and interpretive devices, progressively expanded the opportunities for using the territory as a resource for formal and informal learning.

The educational strategy sought to connect scientific research, local heritage and school curricula through access to specialised laboratories, scientific mentoring and field-based activities. The School Participatory Budget projects developed in 2017 preceded the generalisation of curricular autonomy and flexibility under Decree-Law 55/2018, while the School Science Network was established before the launch of the national *Ciência Viva* School Clubs programme in 2018. The local experience was subsequently acknowledged as an inspiration for the national initiative (Geoparque Litoral de Viana do Castelo, 2021).

The significance of this approach lies particularly in the provision of shared scientific and territorial resources that individual schools might otherwise find difficult to access. Laboratories, field equipment, classified geosites, interpretive facilities and technical support provided opportunities for developing educational activities connected to local geological and environmental characteristics.

The 2025 survey of school leaders provides additional context for assessing these arrangements (Sousa-Pereira & Carvalhido, 2025). Most respondents considered municipal support conditions important or decisive for curricular flexibility (74%) and rated cooperation with the Municipal Support Team as effective or very effective (70%). However, perceptions of the Promoter Teams for Curricular Differentiation and Flexibility were more heterogeneous, with 56% reporting a reduced or null impact on school dynamics.

These differences suggest that the availability of shared resources and their effective integration into school practices represent distinct dimensions of educational implementation. Organisational constraints, including timetables, class sizes and resource availability, may limit the continuity of interdisciplinary activities even where scientific infrastructure and municipal support are available. This interpretation remains exploratory and requires further investigation, particularly because the survey addressed broader educational policies rather than the specific contribution of the aspiring geopark.

The monitoring records complement these perceptions by documenting substantial differences in the use of scientific and interpretive infrastructure. Laboratory participation recovered after the COVID-19 pandemic, but activity became increasingly concentrated in the native-species propagation laboratory. Similarly, organised groups represented approximately 71% of recorded visits to the Argas Gateway and 74% to the Neiva Gateway, indicating the importance of organised activities within the recorded use of these facilities.

The contrasting trajectories of digital resources also deserve attention. While website use increased between 2021 and 2023, mobile application use declined after its initial year. These patterns may inform future decisions concerning communication strategies and the allocation of resources, although differences in measurement procedures and user behaviour prevent direct comparisons between platforms.

Taken together, these results demonstrate that the establishment of infrastructure does not necessarily lead to uniform or sustained use. Differences between facilities may reflect their functions, accessibility, educational programming, operational conditions and the characteristics of their potential users. Regular monitoring is therefore important not only for documenting participation but also for identifying underused resources and supporting adjustments to educational and interpretive programmes.

However, the available indicators primarily measure activities and interactions rather than educational outcomes. Laboratory users, field-trip participants, gateway visitors and digital accesses provide information on the use of resources, but they do not establish improvements in geological literacy, learning achievements or public understanding of geoheritage. Future assessments would benefit from combining these monitoring indicators with educational evaluation and visitor studies.

6.3. Opportunities and challenges of municipal-scale geopark governance

The Viana do Castelo experience also illustrates both the opportunities and the challenges associated with developing an aspiring geopark at the municipal scale. The involvement of local authorities enabled the progressive integration of geoheritage conservation with education, scientific infrastructure, environmental management and territorial interpretation.

Municipal governance may facilitate coordination between different policy areas and provide access to administrative, technical and financial resources. In Viana do Castelo, the development of the project involved scientific institutions, schools, parish councils, community organisations and private stakeholders, creating opportunities for cooperation across sectors. As illustrated by Arouca UNESCO Global Geopark (Rocha *et al.*, 2010), a single-municipality territory can support a geopark governance model, although its effectiveness depends on the specific institutional arrangements, resources and stakeholder participation mechanisms established.

The transition from an association-based structure to direct municipal management in 2024 represents a particularly significant institutional change. The establishment of a Specialised Technical Team and a Municipal Council of the Geopark, together with formal cooperation arrangements involving the 27 parish councils and unions, maintained institutional channels for participation and coordination.

Nevertheless, the existence of formal participation mechanisms does not necessarily demonstrate effective stakeholder involvement or continuity in decision-making. The long-term implications of municipalisation will depend on the stability of management arrangements, the availability of resources and the capacity to maintain cooperation between scientific institutions, local communities and other stakeholders.

The management of geological heritage across different land-tenure regimes represents an additional challenge. The thirteen Local Natural Monuments include public, private and community-managed land, requiring different forms of cooperation and intervention. Agreements with parish councils and commons' management bodies provide mechanisms for involving local stakeholders, while restoration and maintenance programmes have sought to extend participation to companies and community organisations.

However, the recorded maintenance activities were concentrated in only four monuments, despite the wider network of cooperation agreements. This uneven implementation highlights the difficulties of ensuring regular conservation activities across a geographically dispersed and institutionally diverse protected-area network.

Financial sustainability constitutes another important consideration. The documented investments demonstrate the mobilisation of municipal resources and competitive funding programmes, but the available financial information does not provide a complete assessment of implementation and recurrent management costs. Long-term maintenance, staffing, monitoring and infrastructure operation may therefore represent significant challenges beyond the initial investment phase.

The integration of the aspiring geopark into broader municipal environmental policies creates additional opportunities for connecting geoconservation with biodiversity conservation, ecological restoration and climate adaptation. Nevertheless, these relationships should be interpreted cautiously, as the implementation of environmental programmes does not necessarily demonstrate measurable improvements in geological heritage conservation.

Several operational limitations identified in the project record also illustrate the challenges of maintaining a diversified infrastructure network. These include laboratories with no recorded bookings, limited digital interaction at some upland monuments, difficulties associated with the location of research facilities in remote areas and the abandonment of a planned fourth gateway.

These circumstances suggest that the long-term sustainability of the aspiring geopark will depend not only on expanding infrastructure but also on adapting existing resources to demonstrated needs and maintaining effective management and monitoring mechanisms.

The prospective application for UNESCO Global Geopark status requires the demonstration of geological heritage of international significance, independently of the legal classification of sites as Local Natural Monuments. A preliminary and as yet unpublished assessment by the application promoter team has identified Montedor and Pedras Ruivas as potentially significant at the international level. However, a systematic comparative assessment has not yet been completed, and further scientific studies are being developed to substantiate the geological significance of the territory. The application will also need to demonstrate compliance with the broader UNESCO criteria concerning conservation, education, sustainable development and management.

The project remains an aspiring geopark, with an application for UNESCO Global Geopark status under preparation. The doc-

umented experience therefore represents an evolving municipal initiative rather than an established model whose long-term effectiveness has already been demonstrated. Nevertheless, it provides an example of how scientific research, statutory geoconservation and territorial governance can be progressively connected within a municipal framework.

6.4. Limitations

The adopted retrospective documentary approach provides an integrated account of the development of the aspiring geopark, but it also imposes limitations on the interpretation of its outcomes. The documentary sources primarily record institutional decisions, activities and investments, rather than independently evaluated conservation, educational or socioeconomic results.

The monitoring datasets differ in their periods of coverage, measurement units and recording procedures. Consequently, their totals cannot be interpreted as numbers of unique individuals across services or years. In addition, the Northern Coast Observatory and Atlantic Gateway share the same visitor series, while QR-code records measure interactions with interpretive devices rather than total visits to geological heritage sites.

The available annual records do not allow seasonal patterns or the causes of changes in infrastructure use to be established. Comparisons between facilities must also consider differences in opening dates, functions, accessibility and monitoring coverage.

The educational evidence derives from a previously published questionnaire involving 23 school leaders, representing 40% of the potential respondents. The limited response coverage, unequal representation of leadership roles and absence of school-level identification restrict the generalisation of these findings. Moreover, the questionnaire addressed national curricular policies and a broader set of municipal support mechanisms, preventing the specific contribution of the aspiring geopark from being isolated.

Accordingly, the present study documents the evolution of institutional arrangements, the implementation of initiatives and the recorded use of infrastructure, but does not independently establish their effects on learning, conservation outcomes, tourism, public legitimacy or sustainable territorial development.

The transferability of the Viana do Castelo experience to other territories must also be considered in relation to their specific legal frameworks, institutional arrangements, financial resources and scientific heritage. To address these limitations, future research should incorporate systematic monitoring of geoheritage conservation status, educational outcomes, visitor experiences and the effectiveness of stakeholder participation, allowing a more comprehensive assessment of the long-term results of municipal-scale geoconservation strategies.

7. Conclusions

The development of the Viana do Castelo Littoral Aspiring Geopark between 2005 and 2025 illustrates how geoscientific research can provide the foundation for a municipal strategy integrating geoheritage conservation, science education and territorial management. Research on the Quaternary and geomorphological evolution of the Minho–Neiva coast, followed by successive geoheritage inventories, supported the legal classification of thirteen Local Natural Monuments in 2016 and 2018. Although initially focused on Quaternary coastal evolution, the successive inventories progressively incorporated geological features representing other periods and processes, extending the scientific scope of the geoconservation strategy. This process demonstrates the importance of sustained scientific investigation and cooperation between research institutions and local authorities in translating geological knowledge into statutory geoconservation measures.

The subsequent development of educational programmes, scientific facilities, interpretive infrastructure and environmental management initiatives progressively extended the role of geological heritage beyond its identification and protection. The territory became a resource for scientific research, formal and informal education, and public interpretation of geological and environmental processes. The Quaternary record provided a particularly relevant interpretive framework, connecting landscape evolution, environmental change and human occupation.

Municipal monitoring records document the use of these resources but also reveal substantial differences between facilities and periods. Together with the published survey of school leaders, these results highlight both the opportunities provided by shared scientific and educational infrastructure and the challenges associated with its sustained integration into educational practices. However, the available evidence does not establish the effects of these initiatives on learning outcomes, conservation effectiveness or sustainable territorial development.

The transition to direct municipal management in 2024 represents a further stage in the institutional development of the aspiring geopark. Although this model provides opportunities for integrating geoconservation into municipal policies and mobilising territorial stakeholders, its long-term sustainability will depend on continued scientific cooperation, stable resources, effective participation and systematic monitoring. Further scientific assessment is already underway to substantiate the international geological significance of the territory in support of a future application for UNESCO Global Geopark designation.

Overall, the Viana do Castelo experience demonstrates how a research-based geoheritage initiative can evolve into a broader framework for municipal territorial governance. Its principal contribution lies in documenting the connections between scientific knowledge, legal protection, education and institutional development, while identifying the need for long-term evaluation of conservation, educational and management outcomes. These findings may inform similar initiatives in other territories, although their applicability will depend on local scientific, institutional and financial conditions.

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Declaration of Interests

The first author has been directly involved in the scientific development and coordination of the Viana do Castelo Littoral Aspiring Geopark, as described in the Materials and methods section. This institutional involvement is disclosed for transparency. The authors declare no other competing interests.

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