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A geotourist route through the Geosites of Cinisi and Terrasini cliffs

Abstract: Agnesi V., Martinello C., Azzara G., Rotigliano E., Conoscenti C., Cappadonia C., *A geotourist route through the Geosites of Cinisi and Terrasini cliffs.* (IT ISSN 0391-9838, 2025). This study evaluates the scientific relevance, quality, and sustainability of a proposed coastal geopath extending for approximately 7 km along the Tyrrhenian coast of northwestern Sicily, between Torre Mulinazzo and Capo Rama, near the towns of Cinisi and Terrasini (Sicily, Italy). The area is characterized by a highly irregular coastline formed by alternating rocky cliffs and sandy beaches, shaped by differential erosion and active tectonics. This geomorphological diversity results in a complex and scenic coastal landscape that hosts significant geological features. A total of 20 sites of geological interest were identified, including three officially recognized geosites and two proposed ones. These sites represent a stratigraphic succession ranging from the Upper Triassic to the Lower Pleistocene, with depositional environments transitioning from shallow to deep marine environments. The proposed route allows for a comprehensive interpretation of the lithostratigraphic, structural, and geomorphological framework of the area within a compact and accessible sector. A quantitative assessment of the geosites was carried out using two established methodologies: the Geosite Assessment Model (GAM) and the method developed by Feuillet and Sourp (2011). Results highlight the high scientific value and uniqueness of the majority of the sites. Only a few, such as the more common beach sectors, scored lower in terms of scientific relevance. Most sites also demonstrated high additional values, including accessibility, aesthetic appeal, and educational potential, due to their proximity to urban centers and supporting infrastructure. Despite urbanization, the presence of protected areas and environmental constraints has helped preserve natural features. The study confirms that the proposed geopath holds strong potential as an outdoor educational laboratory and a sustainable geotourism resource. The development of sea-based services is recommended to enhance accessibility to coastal sites not reachable by land, fostering broader community involvement.

Key words: Integrated geopath, Sicily, Triassic, Pleistocene, Cliffs.

Riassunto: Agnesi V., Martinello C., Azzara G., Rotigliano E., Conoscenti C., Cappadonia C., *Un percorso geoturistico attraverso i Geositi delle scogliere di Cinisi e Terrasini.* (IT ISSN 0391-9838, 2025). Il presente contributo analizza la rilevanza scientifica, la qualità e la sostenibilità di un percorso di geositi proposto lungo un tratto di circa 7 km del litorale tirrenico della Sicilia nord-occidentale, compreso tra Torre Mulinazzo e Capo Rama, nei pressi dei centri urbani di Cinisi e Terrasini (Sicilia, Italia). Questo settore costiero si contraddistingue per una morfologia fortemente articolata, frutto dell'alternanza di falesie rocciose e arenili sabbiosi, modellata dall'interazione tra processi erosivi differenziali e tettonica attiva. Tale complessità geomorfologica conferisce al paesaggio un elevato pregio scenico e un notevole interesse geologico. Sono stati individuati complessivamente 20 siti di interesse geologico, tra cui tre geositi ufficialmente riconosciuti e due proposti. Essi documentano una successione stratigrafica che si estende dal Triassico superiore al Pleistocene inferiore, con ambienti deposizionali che variano da contesti marino-costieri poco profondi a bacini marini profondi. Il percorso proposto consente una lettura integrata del quadro litostratigrafico, strutturale e geomorfologico del settore in esame, all'interno di un'area territorialmente contenuta e facilmente accessibile. La valutazione quantitativa dei siti è stata condotta attraverso l'applicazione di due metodologie consolidate: il Geosite Assessment Model (GAM) e il metodo elaborato da Feuillet e Sourp (2011). I risultati evidenziano l'elevato valore scientifico e la singolarità della maggior parte dei siti selezionati; solo alcune spiagge di tipo più comune hanno riportato punteggi inferiori. Il valore aggiunto complessivo risulta elevato, grazie alla fruibilità, alla valenza paesaggistica e al potenziale educativo, amplificati dalla prossimità ai centri abitati e alla presenza di infrastrutture ricettive. Nonostante la moderata urbanizzazione, i vincoli ambientali e la presenza di aree protette hanno garantito la conservazione delle principali peculiarità naturali. Lo studio conferma il potenziale del percorso dei geositi quale laboratorio didattico all'aperto e risorsa per un geoturismo sostenibile. Si auspica infine l'implementazione di servizi via mare per favorire l'accesso ai siti costieri non raggiungibili da terra, promuovendo una gestione partecipata e integrata a livello locale

Termini chiave: Geopercorso integrato, Sicilia, Triassico, Pleistocene, Scogliere.

INTRODUCTION

Among several types of tourism, Geoturism is associated with attractive and interesting geological destinations and is aimed at emphasising the sustainable use of geosites. Geoturism is defined as a form of natural-based

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tourism that focuses on geology and landscape aimed at promoting sites of geological interest, conservation of geo-diversity, and the knowledge of earth sciences through appreciation and learning. To achieve these goals, the activities of geoturism must include visits to geological features, the definition of geological paths and viewpoints, the creation of associated tools such as guided tours, geoactivities, visitor centres and collaborated events such as conventions and seminars, extraordinary openings, and activities in collaboration with scientific and territorial institutions (Newsome and Dowling, 2010; Dowling, 2011). The development of this type of tourism is closely linked to the implementation of instruments for the promotion and protection of the territory. Protection tools may be established by local or regional authorities and naturalistic associations, as well as by national governments and international organizations. Their goal is both to preserve and promote nature and its landscape, and to enhance awareness and understanding of Earth's resources and uniqueness. This is especially important in light of the growing need to mitigate the effects of climate change and to reduce risks related to natural hazards. These include UNESCO Global Geoparks (UGGp) designed as single areas of international geological significance managed for protection, education and sustainable development but also Nature Reserves like protected areas that also feature geological interest or, again, the Sites of Community Importance (SCIs), the Special Areas of Conservation (SACs) and the Special Protection Areas (SPAs) which are the main nodes of the Natura 2000 network. In this framework, the same groups and organizations have developed guidelines and activities aimed at the identification, evaluation and establishment of geosites. According to one of the first accepted definitions "a geosite can be defined as a site location area or territory in which it is possible to identify a geological or geomorphological interest for conservation" (Wimbledon *et al.*, 1995) but also "Geosites are portions of the geosphere that present a particular importance for the comprehension of Earth history" (Reynard, 2004). In a perspective that sees geosites as a tool for awareness of geological heritage, some authors highlight the difference between geosites, as strictly related to geoheritage, and geodiversity sites, more directly related to geotourism (Brilha, 2016). On the other hand, UNESCO includes within Geoparks a network of geosites as places of strong scientific and touristic attractiveness, as well as places suitable for educational and dissemination activities. Moreover, a geosite indeed represents a new and direct tool for safeguarding and protecting areas of important geological interest, with a more immediate and administratively lighter perspective than other forms of protection such as Parks or Natural Reserves establishment.

The conservation and enhancement of geosites provide for the creation of inventories and assessment of these areas of geological interest (Ferrando *et al.*, 2021). The methodological approach entails a first stage of recognition and selection based on scientific interests, representativeness, and spatial distribution according to several approaches defined in the literature regarding the selection and mapping (Reynard and Panizza, 2005; Fuertes-Gutiérrez and Fernández-Martínez, 2010; Bollati *et al.*, 2012; Brilha, 2016; Reynard *et al.*, 2021; Coratza *et al.*, 2021). The next stage involves the quantitative assessment and, where appropriate, the evaluation of the related risk to the degradation of the selected geosites. Several methods for the quantitative assessment of geosites are proposed in the literature (Pralong, 2005; Reynard *et al.*, 2007; Zouros, 2007; Feuillet and Sourp, 2011; Vujičić *et al.*, 2011; Migoń and Pijet-Migoń, 2017), and many of these considers three main values and corresponding criteria: scientific value (scientific aspects of the sites and their assessment), additional values (natural and cultural aspects), and use value (fruition of geosites by society). To promote geotourism through the identification and evaluation of existing or potential geosites, it is necessary to assess their current status and value, which requires a quantitative method suitable for a proper and objective tourist evaluation.

Feuillet and Sourp (2011) proposed an example of the assessment and promotion of geoheritage based on a "management score" and a "tourism score" to define among some geomorphosites those with the highest priority for management and tourism using a hierarchical ascendant classification in three main groups: "High priority", "Medium priority", and "Low priority". In this view, the Geosite Assessment Model (GAM) developed by Vujičić *et al.* (2011) could allow for assessing the leading values that characterize the geosites as well as their potential for geotourism development (Višnić *et al.*, 2016). Both methods could be useful tools for the planning and management of natural heritage sites and for a more systematic framing of geosites within the framework of geotourism. These papers provide a tool for the protection and conservation of areas of geological interest but also allow targeting priority geosites in terms of both management and tourism issues by the application of various methods for the quantitative assessment of geoheritage.

Also in Italy, in recent years, a tendency has been affirmed to identify and propose the establishment of geological routes, at the local, national or international levels, linking a set of geosites so to furnish a complete reading of the geological processes, affecting the territory (e.g., Bollati *et al.*, 2012; Pelfini and Bollati, 2014; Agnesi *et al.*, 2017, Cappadonia *et al.*, 2018; Piacentini *et al.*, 2019; Selmi *et al.*, 2019; Coratza *et al.*, 2019; Santangelo *et al.*, 2020; Cafiso *et al.*, 2021, Valentini *et al.*, 2022).

Sicily (Southern Italy) includes a rich variety of elements of natural and cultural interest, attracting many tourists, also thanks to its mild Mediterranean climate. In Sicily, there are two of the 213 Geoparks found by UNESCO in 48 countries, numerous nature reserve areas and Natura 2000 sites, as well as about 40 geosites already established by the regional government. However, the great potential of Sicily's geological heritage is still not sufficiently exploited to attract tourists and visitors, especially in coastal areas, where careful management could both increase tourism and strengthen efforts to safeguard the environmental heritage.

This paper aims to create a route which connects twenty different sites of geological interest, whose potentialities were assessed by using two approaches (Feuillet and Sourp, 2011; Vujičić *et al.*, 2011). In fact, all the geosites are located along a spectacular and attractive coastal sector of northern Sicily, which is visited by more than 250.000 tourists per year. Connecting the twenty geosites through the perspective of the geological history and geomorphological processes of this important coastal sector of Sicily offers an integrated route which merges cultural and touristic values.

STUDY AREA

The area is located about 25 km west of Palermo, along the eastern edge of the Gulf of Castellammare in the northern coast of Sicily, Italy (fig. 1a). It includes a coastal sector of approximately 33 km (Agnesi *et al.*, 2017; Di Maggio *et al.*, 2017).

The sector is located within the territories of the municipalities of Cinisi and Terrasini (Palermo). Cinisi (12,127 inhabitants, 75 m a.s.l.) is a town of medieval origin, dating back to the period of Islamic domination in Sicily (9th-11th century) (Idrisi, 1154). It was a fiefdom of the Abbey of *San Martino delle Scale* and developed around a fortified convent. Terrasini (13,063 inhabitants, 33 m a.s.l.) is a more recent settlement, originating in the 17th century around its main church. However, the *Terrasinorum* (from the Latin *land of the marine coves*) district was already mentioned in 13th century documents. In 1832, the coastal village of *Favarotta* was annexed to the territory of Terrasini.

The proposed route covers a coastal sector of approximately 7 km, extending from *Torre Mulinazzo* to *Capo Rama* (fig. 1b). The coastal alternates steep rocky cliffs and sandy beaches, resulting in a highly indented and irregular coastal morphology. This sector represents one of the most remarkable coastal landscapes in Sicily, not only due to its scenic value but also for its notable geological and geomorphological features, which contribute to its strong appeal for geotourism and environmental education.

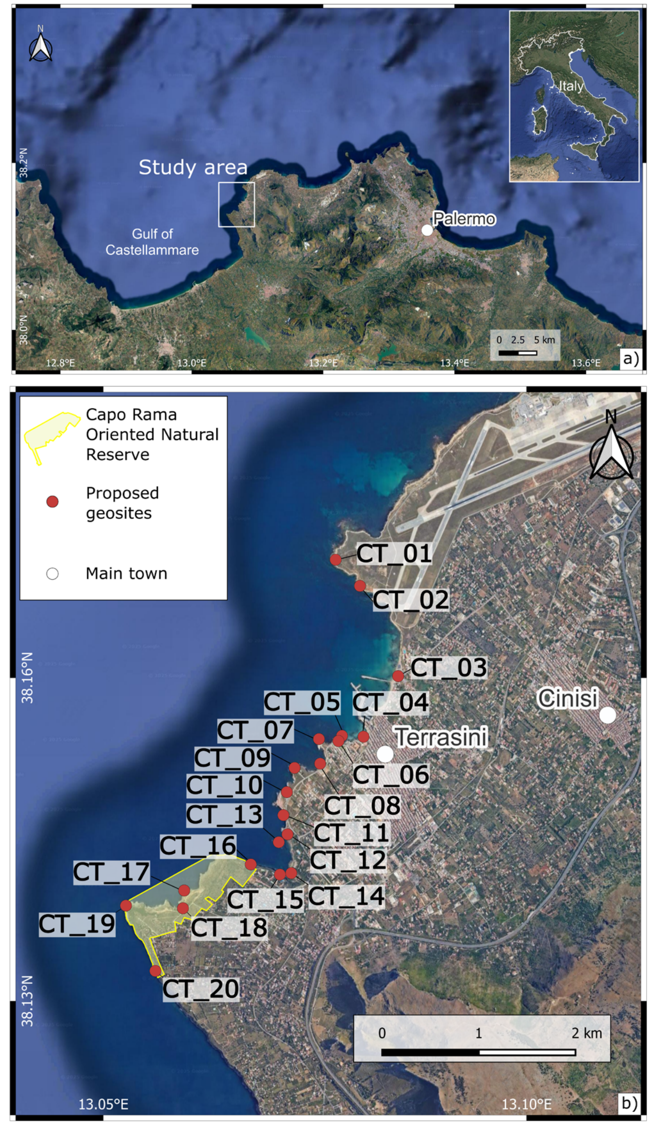

Figure 1 - a) Location of study area and b) of the proposed geopath of Cinisi and Terrasini cliffs. The proposed sites are shown in the figure using the code CT (Cinisi-Terrasini), followed by a progressive number from north to south (see further in the text).

The territory is highly anthropized, being characterized, from west to east, by a) the Falcone-Borsellino Palermo Airport, located on the Punta Raisi coastal plain; b) the town of Terrasini, with its harbour; c) many residential buildings. Despite this human influence, the coastal area retains significant natural features, thanks to the presence of cliffs that have limited human exploitation of the coastline. Moreover, in the easternmost sector, the Capo Rama Oriented Natural Reserve protects a large part of the study area.

Geological and Geomorphological Framework

The area belongs to the Palermo Mountains, in the central-western sector of the Sicilian Chain. It was formed during the Miocene compressional tectonic phases and subsequently displaced by Plio-Pleistocene tectonic activity. The exposed rock formations primarily belong to the *Panormide* carbonate platform, ranging in age from the Upper Triassic to the Lower Pleistocene, spanning approximately 200 million years (Gasparo Morticelli *et al.*, 2023).

The morphology of the territory is characterized by an extended flat area, with elevations ranging from 20 to 100 m a.s.l. This surface corresponds to a wave-cut platform carved into marly limestone and calcarenitic limestone formations. To the east and southeast, the platform is bordered by a large amphitheater-shaped structure formed by the slopes of limestone mountains, at the base of which extensive debris cones and the broad alluvial fan of the Furi Valley are present.

The platform is bordered by cliffs, whose morphology – either straight or jagged – is strongly influenced by the different lithologies in which they are carved. The continuity of the cliffs is occasionally interrupted by sandy or pebbly beaches.

According to the most recent geological interpretations (Gasparo Morticelli *et al.*, 2023), the following rocks outcrop in the area (fig. 2):

a) Cemented deposits (*Capo Plaia Synthem* - Acronyms: AFL): landslide deposits, alluvial canalized deposits and fluvial terraces, constitutes by gravels, sands and silts, poor cemented eluvial products and colluvial deposits with paleosoils, aeolian deposits. The lower boundary is a subaerial erosional unconformity onto *Raffo Rosso Synthem* (RFR). The upper boundary is represented by the present-day topographic surface. Age: Upper Pleistocene-Holocene.
b) Stratified detritus (*Raffo Rosso Synthem* - Acronyms: RFR): scree cone, stratified detritus and poor sorted subrounded and angular pebbles and boulders materials, alternating with paleosols, aeolian deposits (sandstones and calcarenites). The lower boundary is a disconformity onto pre-Quaternary and Quaternary deposits; the upper boundary is the subaerial erosional unconformity at the base of *Capo Plaia Synthem* or the actual paleosol horizon. Age: Upper Pleistocene.
c) Calcarenites and sands of Castellammare (*Marsala Synthem* - Acronyms: MRSc): reddish-yellow biocalcarenites in decimetric layers, with cross-stratification, foraminifera, and algal fragments; conglomerates with an arenitic matrix and white silty sands containing lamellibranchs (*Pecten sp.*, *Chlamys sp.*, *Ostrea sp.*, *Cardium sp.*) and gastropods. Locally, cemented tempestites. Depositional environment: neritic-coastal Age: Lower Pleistocene (Calabrian).
d) Brown pelites (*Numidian Flysch* - Acronyms: FYN_2): pelites, sometimes with manganese, with plane-parallel lamination and *Globorotalia opima* microfauna, alternating with silts, fine-grained sandstones, quartzarenites, and quartz-rich conglomerates. Depositional environment: escarpment to basin. Age: Upper Oligocene-Lower Miocene.
e) Calcilutites and marls (*Amerillo Formation*, commonly referred to in geological literature as *Scaglia* - Acronyms: AMM): calcilutites and white to red-greyish marls with planktonic foraminifera alternating with Orbitoid calcarenites and rudist fragments. Depositional environment: pelagic and escarpment. Age: Upper Cretaceous-Eocene. In the Cala Rossa area, *Scaglia* unconformably overlies calcarenites and calcilutites with brachiopods and radiolarites of Middle-Upper Liassic age (*Buccheri Formation*).
f) Limestone and calcarenites (*Piano Battaglia limestone* - Acronyms: PNB_b): coralgal biolitites, calcarenites and calcirudites with *Ellipsactinia sp.*, molluscs (*Nerinea sp.*,), echinoids, rare ammonites, oolitic calcarenites. Lower boundary is unconformity on *Buccheri Formation*. Depositional environment: carbonate platform margin and upper slope environment.
g) Calcarenites and calcilutites (*Buccheri formation* - Acronyms: BCH): calcarenites and calcilutites with brachiopods, calcarenites with crinoids and echinoids fragments; greyish nodulat limestones and red calcilutites, with ammonites and belemnites. Depositional environmental: pelagic platform and depositional slope. Age: Upper Liassic-Malm.
h) Megalodontid dolomitic limestones (*Capo Rama Formation* - Acronyms: RMF): limestones with megalodonts, coral and algal biolithites, dolomites, and loferitic breccias, arranged in shallowing-upward cycles (peritidal and subtidal). Depositional environment: back-reef lagoon and tidal plain. Age: Upper Triassic-Lower Liassic.

The geometric relationships between these rock formations include both tectonic contacts (e.g., RMF overriding FYN_2 and AMM) and stratigraphic contacts (e.g., MRSc overlying FYN_2 and AMM).

Evidence of extensional tectonics is observed in the active cliffs and large fault escarpments. This tectonic phase, responsible for the displacement of Meso-Cenozoic rocks, has been dated to approximately 1.5 million years ago, based on the deposition of Lower Pleistocene calcarenites above them. Post-Tyrrhenian uplift rates, calculated from the elevation of marine terraces, range between 0.1 and 0.2 m/year (Di Maggio *et al.*, 2017).

MATERIALS

The geotourist route through the Geosites of Cinisi and Terrasini cliffs aims to connect multiple geosites (some formally established) through a pathway which allows a geological reading of the territory and its evolution, and promote its enhancement, also to implement the geotouristic value of the area. The selection of geosites started from the first stage of

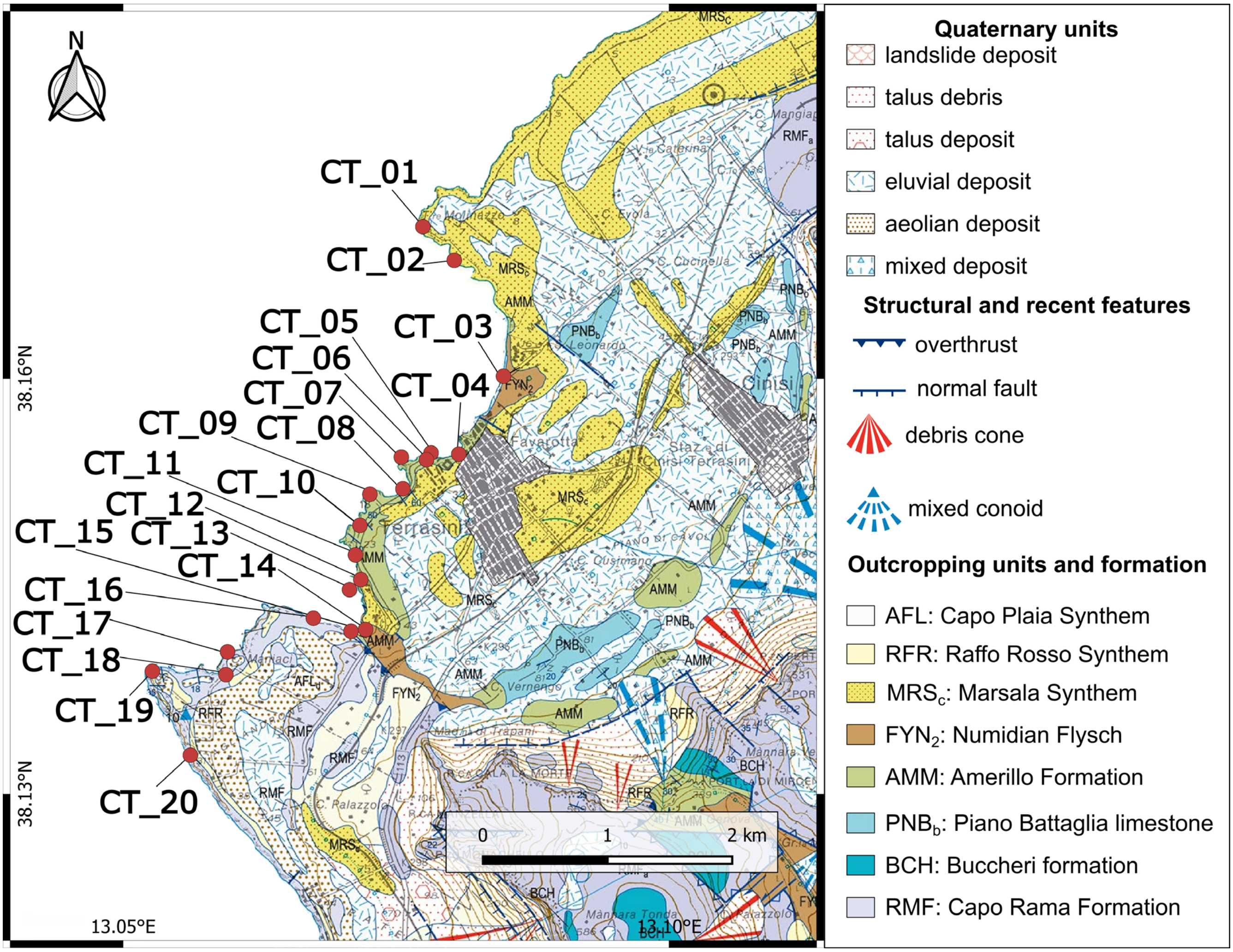

Figure 2 - Geological map of the study area (modified from Servizio Geologico, 2023).

collecting data from existing literature and documents about the state of the studied territory, including existing protected areas and geosites. This resulted in the 20 potential geosites, which were selected based on scientific interest (geological, geomorphological, paleontological and paleogeographic) as well as the representativeness of the related processes. Regarding the scientific interest, a first criterion is genetic, considering the landforms characteristic of the coastal belt (a set of rocky coasts) and the geological setting of this sector of the Sicilian Chain; the balance in the spatial distribution of the geomorphological features in the study area has also been considered. Other factors, such as tourist and cultural vocation and accessibility, were also considered.

Description of the selected geosites

The geotourist route through the Geosites of Cinisi and Terrasini cliffs intercepting 20 potential geosites from Torre Mulinazzo to Capo Rama (named from CT_01 to CT_20, see figs 1, 2 and supplementary materials). The set of geosites allows to reconstruct the sequence of geological and geomorphological events that led to the current landscape and the effects of active processes of the morphodynamics of the rocky coasts.

The route starts from the *Torre Mulinazzo* peninsula (CT_01 - fig. 3a), whose name derives from the coastal tower located there. This tower, characterized by a quadrangular plan, is part of a coastal defense and communication system built to counter incursions by Saracen pirates' raids from North African. Its construction certainly dates back to before the 16th century, with the first historical documentation of its existence dating to 1578.

The first section features a coastal cliff carved into the *Marsala Synthem* calcarenites, where the alternation of calcarenite and sandy levels is observable. Small bays, known as *le calette* (CT_02 - fig. 3a), provide landing points and a direct view of the stratigraphic sequences. The area is accessible only from the sea, as the coastal plain sector hosts the Palermo Airport and is interdicted to people. The cliff extends for approximately 950 m with a NW-SE orientation.

In its southern section, the calcarenites unconformably overlie the *Scaglia* and the clays of the *Numidian Flysch* (Cipolla, 1978; Servizio Geologico, 2023). However, in recent years, this contact has become obscured due to the construction of a breakwater composed of large boulders. The cliff is included among the sites of geological interest in the metropolitan area of Palermo, as designated by the Sicilian Regional Council (Resolution No. 6 of 21/01/2016). It is classified as a geosite of stratigraphic interest under the name *Successione Plio-Pleistocenica di Magaggiari* (Magaggiari Plio-Pleistocene Succession), with the acronym NAT-6CJ-5933.

At the end of the cliff, there is a sandy beach (CT_03) composed mainly of quartz grains and fragments of extant mollusc shells. It has an NNE-SSW orientation and extends for approximately 450 m, reaching the town of Terrasini. The beach has undergone significant modifications due to the construction of the harbor of Terrasini. The beach, known as *La Ciucca*, derives its name from the Arabic *suqqah*, meaning "long strip of cloth". Another name, *Magaggiari*, originates from the Arabic *mahğar*, meaning "stony place", likely referring to the abundant lithic fragments covering the calcarenitic outcrops immediately behind the sandy shoreline (Catalfio and La Duca, 2010). The analysis of cartographic data and historical photographs indicates that the beach was originally a long and continuous strip, bordered landward by an inactive cliff carved into calcarenites. Over the last century, these calcarenites have been extensively quarried as construction materials, leading to the exposure of the *Numidian Flysch* clays. The contact between the calcarenites and the Flysch pelites plays a key role in the presence of a small spring, which emerges due to the permeability contrast between the two formations. This spring is responsible for the name of the first urban settlement in the area, *Favarotta* (from the Arabic *fawara*, meaning "spring"), which supplied water to a village fountain until approximately fifty years ago. In the southern sector, the low sandy coast transitions into a short stretch of inactive cliff carved into the *Scaglia*. Until the mid-20th century, this area marked the mouth of the *Torrente Furi*, a stream originating from the limestone mountains behind the town of Cinisi and crossing the wave-cut platform. Extensive urban development in Terrasini, particularly following the construction of the harbor, has significantly modified the morphological setting of the area. After the 1950s, the stream was confined to an artificial channel and later diverted into a culvert beneath the town. However, the underground channel has not always been able to accommodate high flow rates, leading to major failures in past decades. Notably, during extreme rainfall events (January 1985 and November 1987), the channel collapsed, resulting in a sinkhole and severe flooding in the lower part of the urban center. The harbor is bordered on its western side by a breakwater. Opposite the breakwater, the *Scaglia* cliffs enclose the area.

Moving southwest, immediately outside the southern breakwater, lies *Praiola beach* (CT_04), a 130 m long sandy beach in front of very shallow sea bottom coast. The beach was partially formed due to artificial nourishment using dredged sands during the harbor's construction. It is backed by a cliff carved into the *Scaglia*. This area is part of the BES (Pocket Beach Management and Remote Surveillance System) project (pocket beach code: SIC26PA13) that provides a specific tool for the management of pocket beaches in terms of the guidelines useful as a model for the correct management of a beach environment (Randazzo *et al.*, 2021).

To the west of *Praiola beach*, the coastline is characterized by sea stacks (CT_05), whose formation is linked to the high erodibility of the calcilutites, further intensified by tectonic deformation. Nowadays, the sea stacks consist of four rocks of different sizes (with a medium height of 2 meter), oriented NNW-SSE direction along a bedding plane.

Beyond this point, a cliff coastal section develops carved into the *Scaglia* (CT_06 and CT_08). The *Scaglia* is extensively deformed by chevron folds and reverse faults, which, due to their varied orientations, have influenced the coastline's response to wave action. The predominant NW-directed wave regime (Mistral) has contributed to the development of a complex cliff morphology, further accentuated by the striking alternation of white and red layers characteristic of the *Scaglia*. This coastal section, spanning approximately 1,500 m to *Cala Rossa Bay*, is among the most spectacular in Sicily. The interplay of geological structures and marine erosion has produced a highly scenic landscape, particularly notable for its sea stacks, best appreciated either from land or by navigating along the coast.

One prominent feature along the cliff is *Punta di Grotta Perciata* (CT_07), a peninsula named after a natural arch (*Perciata* meaning "pierced" in the Sicilian language). This arch results from the differential erosion of a calcarenite layer, which lies in angular unconformity over the sub-vertically oriented *Scaglia* strata (fig. 3b). Local tradition reports that the poet Giovanni Meli (1740-1815), a key figure in the Arcadian literary movement, frequently visited *Grotta Perciata*. It is said that he composed some of his most famous works here, inspired by the seascape and reinterpreting classical Sicilian myths in the Sicilian language (Agnesi *et al.*, 2007).

Further southward along the coast, *Torre Alba* or *Fanara* (CT_09) stands as part of the historic coastal watchtower system, built to defend Sicily's shores. The earliest records of this tower date back to 1586. At the *Torre Alba* site, the Pleistocene marine abrasion platform can be observed, where an erosion surface truncates the highly tectonized *Scaglia* layers (fig. 3c).

The route beyond the *Torre Alba* site features a cliff carved into the *Scaglia* (CT_10). Its complex morphology, shaped by Plio-Pleistocene faulting, is distinguished by the presence of two little picturesque inlets.

The cliff culminates at *Cala Rossa Bay*, one of the most iconic sections of the Palermo coastline due to its outstanding landscape and environmental significance. The bay is renowned as one of the most picturesque sites on the western Sicilian coast. *Cala Rossa*, extending over 750 m inland, represents the most prominent bay in this section of the coastline. Its formation is controlled by tectonic activity and differential marine erosion, which have led to distinct morphological developments on either side of the bay. At its center, a small islet enhances the scenic appeal of the area. The bay's orientation follows a major tectonic fault, marking a thrust plane where

Figure 3 - a) Torre Mulinazzo and the Calette. Credit: Marcello Consiglio; b) The Perciata Cave: angular unconformity between the Pleistocene sandstones and conglomerates (MRSc) and the subvertical succession of white calcilutites with planktonic foraminifera (AMM). Credit: Chiara Martinello; c) The succession of Scaglia at Torre Alba. Credit: Anna Vitale; d) The Cala Rossa landscape. In the image, it is possible to observe the islet (on the left), the Cala Rossa beach (in the central part), and the cliff carved into the Mesozoic limestone. Credit: Marcello Consiglio; e) The continental succession at CT_12: 1) Scaglia, 2) conglomerates and breccias, 3) paleosol, 4) Marsala calcarenites. Credit: Marcello Consiglio; f) The Cala Rossa Bay with the normal fault contact between the Capo Rama Formation and the Scaglia (in the white box) and the Isolotto. Credit: Marcello Consiglio.

the platform limestones of the *Capo Rama* overthrust the *Numidian Flysch* succession, which in turn overlies the calcilutites of the *Scaglia*. As a result, the maximum coastal retreat has occurred in areas where the clays are exposed (fig. 3d).

On the eastern side of the bay (CT_11), a more articulated cliff emerges, less steep and more irregular due to the geomorphological arrangement of the layers carved into the *Scaglia*. Further along (CT_12), the cliff transitions into Pleistocene calcarenite layers, preserved in angular unconformity with the *Scaglia*, which have been affected by erosion and rockfalls.

Locally, between the *Scaglia* and the *Marsala Synthem* calcarenites, a continental succession crops out, consisting of conglomerates and breccias underlying a paleosol of Early Pleistocene age (fig. 3e).

Off the eastern side, the *Isolotto* (a small islet - CT_13) provides a complete stratigraphic record of the Jurassic-Eocene succession. At its base, radiolarites, crinoidal limestones, and calpionellid limestones are overlain by the distinctive white and red calcilutites of the *Scaglia* (Catalano *et al.*, 1973).

The innermost part of the bay is characterized by outcropping *Numidian Flysch* clays. Due to their higher erodibility compared to the surrounding rocks, these clays have contributed to the formation of the gravelly-pebbly pocket beach (CT_14) of *Cala Rossa* (fig. 3f).

On the western side, a normal fault contact between the platform limestones of the *Capo Rama* Formation and the *Scaglia* can be observed (CT_15). Further along, the coastline features a sub-vertical cliff with a straight profile, sculpted into platform limestones. At its base, a well-developed wave-cut notch (CT_16) is present.

This geological setting illustrates how sedimentary rocks, formed in paleogeographically distinct depositional environments (carbonate platform and basin) at different times, were deformed and thrust over one another during the compressive Cenozoic tectonic phases, shaping the current geological structure. Due to these characteristics, *Cala Rossa* is a site of exceptional geological (both structural and stratigraphic) and geomorphological interest, with significant educational value and outstanding scenic appeal *Cala Rossa* Bay is listed among the sites of geological interest in the province of Palermo (Sicilian Regional Council, Resolution No. 6 of 21/01/2016) as a geosite of stratigraphic significance, registered under the name *Cala Rossa*, acronym NAT-6TE-5604.

From *Cala Rossa* to *Capo Rama*, the coastline is marked by a high, sub-vertical cliff with a tidal notch at its base, carved into the platform limestones (CT_17; fig. 4a). The longitudinal profile of the cliff is relatively uniform, though interrupted by small bays, the largest of which, *Cala Porro* (CT_18), is associated with the presence of reverse faults.

The route concludes at the *Capo Rama* site (CT_19), characterised by outcropping Mesozoic platform limestones. The coastline features steep cliffs and escarpments, while the summit abrasion platform is extensively affected by karst processes, which have led to the formation of numerous *karren* landforms. *Capo Rama* is also notable for the presence of a circular watchtower dating back to the early 1400s, the oldest man-made structure along the route, which serves as the emblem of the Natural Reserve (fig. 4b).

In the *Capo Rama* area, immediately west of the promontory, lies the *Grotta dei Nassi* (PT_20, fig. 4c), a sea cave carved into the Mesozoic platform limestones of the *Capo Rama* Formation. The cave extends for approximately 60 meters and contains a small pebble beach inside. Pottery fragments dating to the Copper and Bronze Ages have been found within the cavity.

This coastal area is protected within the *Capo Rama Oriented Natural Reserve*, established by the Sicilian Region in 2000 (DR 274/44 of 23/06/2000). Within the Natural Reserve, ARTA, through Decree No. 106 of 15/04/2015, has designated three geosites: a) *Triassic sequence of Capo Rama* – of scientific stratigraphic interest, with a national-level significance; b) *Cala Porro cave* – of scientific speleological interest, with regional-level significance; c) *Nassi cave* – of scientific speleological interest, with regional-level significance.

The coastal area where the sites CT07 to CT20 are located is entirely included within the Site of Community Importance (S.I.C.) "Cala Rossa and Capo Rama", code ITA020009, designated under the 92/43/EEC Directive (Habitat Directive) because of the high landscape, floristic and phytocenotic interest. In addition, some interesting floristic elements give this territory a significant phytogeographical interest (D Zone), as well as the Capo Rama also plays a fundamental role as a migration route and resting place for birds in spring and autumn.

Finally, along the Terrasini promenade near *Praiola* Beach stands the Regional Museum of Palazzo d'Aumale, an important naturalistic, archaeological, and ethno-anthropological institution established by the Sicilian Region in 2001. The museum is housed within an architectural complex built in 1835 as a storage facility for the wine produced by Henri d'Orléans, Duke of Aumale and son of King Louis Philippe of France, in his Zucco estate. The museum hosts significant geological and natural history collections that illustrate the physical characteristics and diverse habitats of the coastal area of the Gulf of Castellammare. Due to its strategic location, the museum is seamlessly integrated into the proposed geological route, serving as a point of synthesis and in-depth exploration of the features observed along the route.

Figure 4 - a) Geosite CT17: sub-vertical cliff with tidal notch carved into the platform limestones. Credit: Anna Vitale; b) The circular watchtower of Capo Rama. Credit: Marcello Consiglio; c) The Grotta dei Nassi. Credit: Marcello Consiglio.

METHODS

Quantitative Assessment of Geosites

For the quantitative evaluation of the 20 selected geosites, the methodologies elaborated by Feuillet and Sourp (2011) and the Geosite Assessment Model (GAM - Vujičić *et al.*, 2011) were used. Both the two methods consider the most common indices defined in the literature (scientific, ecological, aesthetic and cultural values) to provide a tool useful for the sustainable planning and management of geologic heritage sites and their transformation into tourism destinations.

For the Feuillet and Sourp (2011) assessment procedure three components are estimated: scientific value (SV), additional value (AV), and Use value (UV). The Scientific value was assessed according to 1) paleo-geomorphological model, 2) rareness, 3) representativeness and 4) integrity criteria, each scored on a scale from 0 to 1, for a maximum score equal to 4. The criteria related to the AV contribute to the geosites assessment in terms of their interaction with the other natural and cultural aspects for a total maximum score of 3. Considering that the study area has a strong tourist appeal, more emphasis was given to Use value that concerns the potential fruition of geosites by visitors in terms of 1) accessibility, 2) visibility, 3) services and 4) importance for education, each scored on a scale from 0 to 0,75, for a maximum score equal to 3. The methodology allows for classification of the geosites in terms of management and tourism promotion through the evaluation of the management rating (MR) and the tourism rating (TR), defined through the following equations:

$$MR = SV + (AV+UV)/2 \quad (1)$$

$$TR = (AV+UV) + (SV/2) \quad (2)$$

The MR index mainly reflects the scientific values and is useful for supporting the site management decision regarding the choice of measures for protection and conservation actions (Cappadonia *et al.*, 2018), whilst the TR index is a useful tool for highlighting, in terms of additional and use values, the more suitable geosites for geotourism and education.

The Geosite Assessment Model (GAM) takes into account the similar criteria, which are actually proposed for the most common assessment methods in the literature, with a specific focus on the touristic potential of the geosites. The GAM structure can be written using the equation (3) and consists of two main components: main values (MV) and additional values (AV), comprising three and two sub-groups of indicators, respectively.

$$GAM = MV + AV \quad (3)$$

MV is the sum of three sub-values: Scientific/Educational Values (VSE), Landscape/Aesthetic Values (VSA), and Protection/Conservation values (VPr); AV, on the other hand, results from the sum of Functional Values (VFn) and Tourist Values (VTr).

According to the original GAM definition MV and AV can be written as follows (Boškov *et al.*, 2015):

$$MV = VSE + VSA + VPr \equiv \sum_{(t=1)}^{12} (SIMV_t)$$

$$\text{where } 0 \leq SIMV_i \leq 1 \quad (4)$$

$$AV = VFn+VTr \equiv \sum_{(t=1)}^{15} (SIAV_t)$$

$$\text{where } 0 \leq SIAV_i \leq 1 \quad (5)$$

SIMV represents the 12 sub-indicators of MV, and SIAV represents 15 sub-indicators of the AV; the assessment of geosites is obtained as the sum of all sub-indicators. For the description and range of values attributable to each indicator, this work refers to the explanatory tables of the original work of Vujičić *et al.* (2011). Then, each sub-indicator was graded from 0 to 1 for each of the 20 geosites selected. After the gosites assessment, the GAM model provides for the creation of a matrix with 15 rows (number of AV sub-indicators) and 12 columns (number of MV sub-indicators) of the obtained main and additional values presented via X and Y axes, respectively. The GAM matrix consists of nine zones indicated by Z(I,j) with i,j = 1,2,3 indicating the relevance of the sub-indicators based on the scoring that is possible for them to have. The different zones, therefore, suggest the peculiarities of the different geosites based on MV and AV, for example, a geosite with MV an AV values equal to 3 and 7, respectively, would be in the field Z12, which indicates the low level of Main Values and a moderate level of Additional Values.

RESULTS

Selection of Geosites

The selection phase was based mainly on scientific interest (geological, geomorphological, paleontological and paleogeographic) and the representativeness of the related processes. Other subsidiary criteria, such as the surrounding landscape and nature, protection level and additional cultural values, were also examined. Always considering the strong tourist vocation of this coastal sector. This approach led to the establishment of a list of geosites, counting 20 sites representative of the principal geological and geomorphological contexts.

Based on the preceding analysis, a marked diversification of coastal morphologies emerges, closely related to the different geological settings of the area. Cliffed coasts are predominant; however, variations in lithological characteristics impart distinct morphological features to each cliff type.

In particular, the cliffs carved into Pleistocene calcarenites are strongly influenced by the sub-horizontal bedding of the strata and the presence of interbedded sandy layers. Cliffs formed in the *Scaglia* Formation, due to the intense tectonic deformation of this lithological complex, appear significantly more irregular and are often punctuated by small sea-level cavities. Conversely, cliffs carved into platform limestones exhibit a more regular profile and are characterized by a well-defined wave-cut notch, often associated in the lower part with a modest vermetid bench. Moreover, the presence of both normal and reverse faults has contributed to the development of small inlets and marine caves along the coastline. In contrast, the overall extent of beach systems is relatively limited. These include both extensive sandy beaches (e.g., *Magaggiari* Beach) and smaller sandy stretches (e.g., *La Praiola* Beach). In the southernmost part of the area, a predominantly pebbly beach (*Cala Rossa*) is present at the head of a small bay. The *Cala Rossa* inlet, whose genesis is linked to the thrusting of platform limestones over the *Scaglia*, provides an excellent educational example of this type of tectonic phenomenon.

Table 1 - General numerical assessment of the 20 selected geosites and their most representative landform.

		Feuillet and Sourp						GAM		
Geosites	Main landform	SV	AV	UV	Total	MR	TR	MV	AV	GAM
CT_01	Low Coastal Cliff	3.00	1.15	0.95	5.10	4.05	3.60	5.75	4.75	10.50
CT_02	Low Coastal Cliff	3.00	0.80	0.95	4.75	3.88	3.25	5.75	4.75	10.50
CT_03	Sandy beach	1.15	0.50	2.75	4.40	2.78	3.83	2.75	7.75	10.50
CT_04	Pocket Beach	2.00	1.25	2.75	6.00	4.00	5.00	4.25	7.75	12.00
CT_05	Sea Stack	4.00	1.20	1.75	6.95	5.50	5.00	6.75	6.50	13.25
CT_06	Plunging Cliff	3.75	1.30	2.75	7.80	5.78	5.93	7.25	7.75	15.00
CT_07	Rocky Coastal Arch	4.00	1.65	3.00	8.65	6.33	6.65	9.00	7.75	16.75
CT_08	Plunging Cliff	4.00	1.50	3.00	8.50	6.25	6.50	8.75	7.75	16.50
CT_09	Plunging Cliff	3.75	1.80	3.00	8.55	6.15	6.68	8.75	7.75	16.50
CT_10	Plunging Cliff	4.00	1.55	3.00	8.55	6.28	6.55	8.25	7.75	16.00
CT_11	Plunging Cliff	4.00	1.55	3.00	8.55	6.28	6.55	8.50	7.75	16.25
CT_12	Rockfalls	3.75	1.55	3.00	8.30	6.03	6.43	8.50	7.75	16.25
CT_13	Islet	4.00	1.55	2.25	7.80	5.90	5.80	7.75	6.50	14.25
CT_14	Pocket Beach	2.50	0.80	2.75	6.05	4.28	4.80	5.25	7.75	13.00
CT_15	Fault Scarp	3.75	1.40	2.65	7.80	5.78	5.93	9.00	7.75	16.75
CT_16	Plunging Cliff	3.75	1.35	2.65	7.75	5.75	5.88	8.75	7.75	16.50
CT_17	Plunging Cliff	3.75	1.35	2.65	7.75	5.75	5.88	8.25	7.75	16.00
CT_18	Plunging Cliff	3.75	1.35	2.65	7.75	5.75	5.88	8.25	7.75	16.00
CT_19	Plunging Cliff	4.00	1.60	2.65	8.25	6.13	6.25	10.50	9.00	19.50
CT_20	Cave	3.75	1.35	0.75	5.85	4.80	3.98	5.50	5.50	11.00

Quantitative Assessment and Ranking of Geosites

The results from the two evaluation methods of the selected geosites are listed in table 1. The table lists the main forms characterising each site and the corresponding values of the indices adopted according to Feuillet and Sourp (2011 - scientific value, SV; additional value, AV; use value, UV; management rating, MR; and tourism rating, TR) and Vujičić *et al.* (2011 - main values, MV; additional values, AV; geosites assessment model values, GAM).

Concerning the assessment of Feulet and Sourp (2011), the outline of the scores enables the comparison of management ranking and tourism ranking in terms of the spatial distribution of the geosites (fig. 5). Fig. 6 shows their graphical representation and helps in individuating a cluster of sites showing the highest scores in both management and tourism rating.

At the same time, the procedure for determining the 12 subindicators of MV and the 15 subindicators of the AV in the GAM model allowed for the construction of the respective matrix (fig. 7). The nine zones of the matrix indicate the peculiarities of the different geosites based on the MV and AV values, highlighting the higher concentration in the Z_{23} and Z_{33} zones, which indicate, respectively, high and very high values both of Main Values and Additional Values. Only two sites fall on the boundary between Z_{21} and Z_{22}, with low to medium values of MV and AV. CT_05 and CT_20 take up the central field of the matrix (Z_{22}) and the site CT_13 ranks on Z_{32} presenting high average values for both MV and AV.

DISCUSSION

The results of the quantitative analysis conducted on the 20 geologically significant sites described above allow for the formulation of the following considerations.

Taking into account the outcomes obtained using the Feuillet and Sourp (2011) method, it can be observed that approximately 70% of the selected sites (from CT_05 to CT_13 and from, CT_15, to CT_19) are characterized by high values (>5) for both the Management Rating (MR - primarily based on scientific values) and the Tourism Rating (TR - mainly based on additional values). This highlights the significant importance of the selected sites, both in terms of their intrinsic scientific value (thus representing excellent field examples for scientific dissemination and education) and their potential for tourism.

The sites CT_01 and CT_02 are characterized by a Lower Pleistocene calcarenitic-sandy succession, rich in fossil content, which, although scientifically interesting, is widespread throughout western Sicily. Furthermore, their

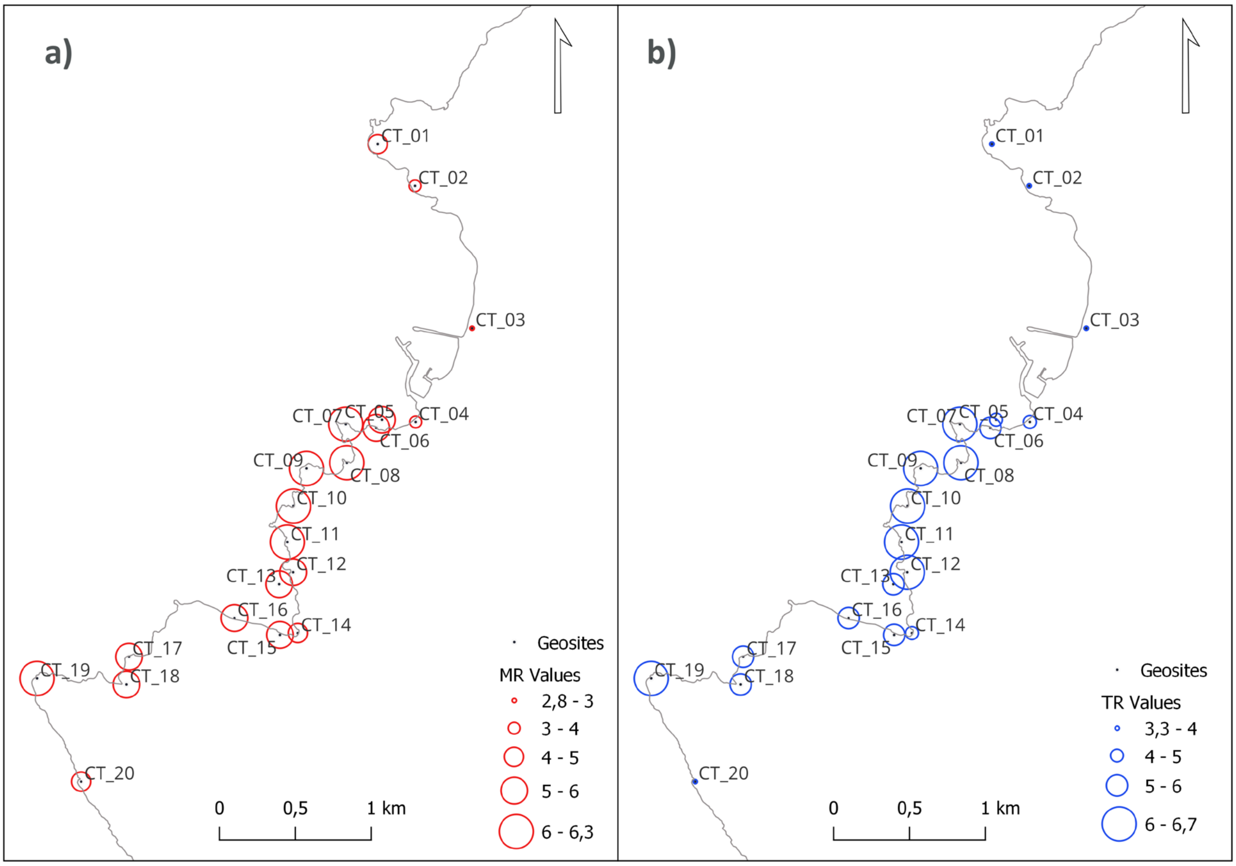

Figure 5 - Geosite distribution according to management ranking (1) and tourism ranking (2).

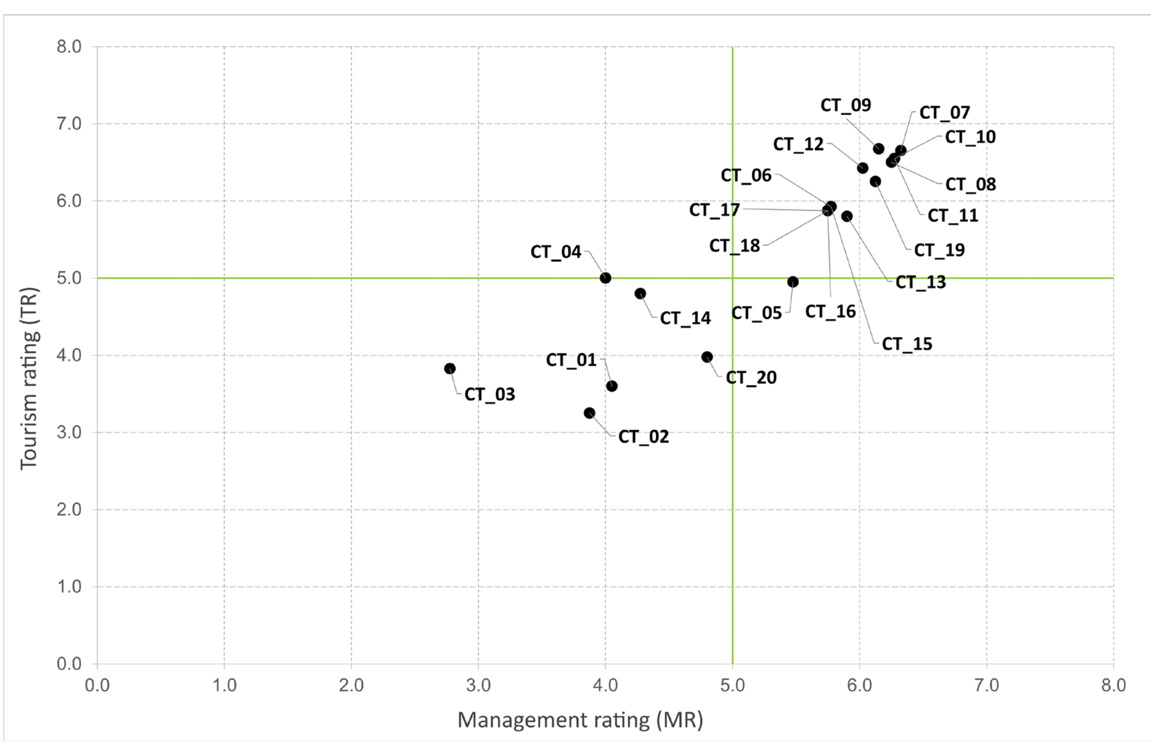

Figure 6 - MR Vs. TR plot for the geosites: the green lines mark the values equal to 5.

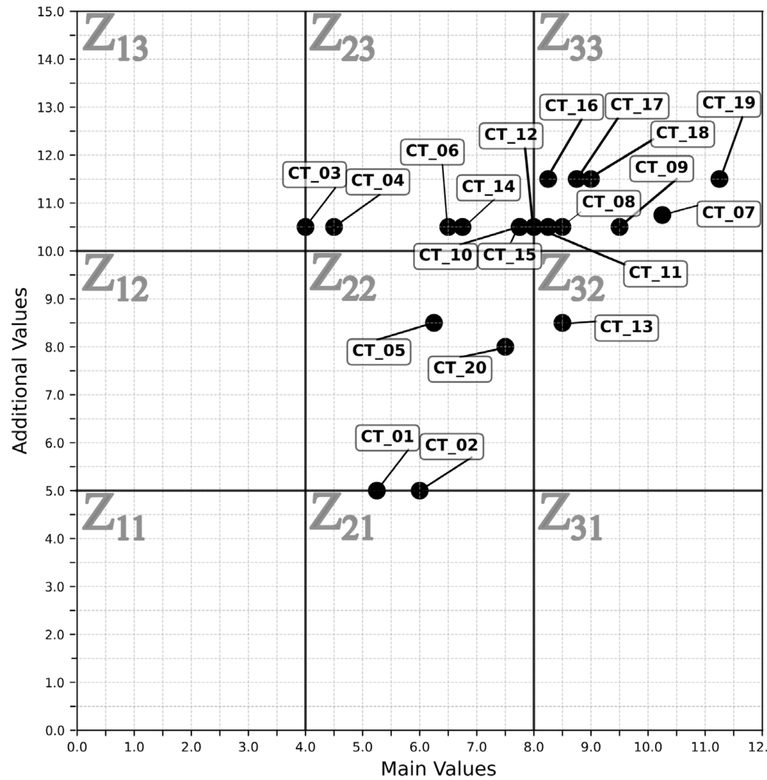

Figure 7 - Placement of geosites in the nine zones of the GAM matrix.

location within the airport perimeter prevents land-based access, rendering them accessible only by sea.

CT_03 refers to the *Maggiari* Beach, an example of a sandy shoreline, which is nonetheless common across Sicily. This beach has also been heavily modified by the construction of a transverse pier and is subject to high tourist pressure, particularly during the summer season. Similar considerations apply to La Praiola Beach (CT_04) and the innermost beach of *Cala Rossa* Bay (CT_14).

Regarding the *Grotta dei Nassi* cave, access is also limited to the sea, which significantly constrains its Additional Values (AV), and consequently its TR score.

The same considerations can be drawn from the results of the GAM method. Nearly 50% of the selected sites (9 out of 20) fall within the Z_{33} quadrant, which includes locations with the highest values of both indices. Supporting the high scientific value of the sites, it is noteworthy that 75% of them are positioned above the median threshold of the Main Value (MV), which is equal to 6. This reinforces and supports the proposal to establish a path of high geological interest encompassing the identified sites.

The lowest MV scores are found at sites CT_03 and CT_04, as they are sandy beaches – a coastal feature quite common along Sicily's northern shoreline. However, these sites represent the only accessible coastal areas available for use by the residents of the towns of Cinisi and Terrasini, as well as tourists, and are therefore associated with high AV values, particularly in terms of accessibility and usability.

Unfortunately, the location of CT_01 and CT_02 within the airport perimeter greatly penalizes their AV scores, despite having average MV values. These sites not only lack direct land access (being reachable solely by sea), but they also offer no logistical or recreational infrastructure support. Conversely, sites CT_05, CT_13, and CT_20, though accessible only from the sea, benefit from logistical support due to their proximity to the urban centers (CT_05, CT_13) or their location within a protected reserve (CT_20).

Finally, the graph clearly shows that, except for sites CT_01 and CT_02, all remaining sites have AV scores above the average value of 8, confirming the general accessibility and, ultimately, the overall usability of the sites.

CONCLUSION

The aim of this study is to assess the quality, scientific validity, and sustainability of a proposed geopath along the coastal area between the towns of Cinisi and Terrasini (Sicily, Italy). Specifically, the authors identified a total of 20 sites of geological interest, including 3 officially recognized geosites and 2 proposed geosites that have not yet been formally established. The proposal to connect these 20 sites stems from the exceptional geological and geomorphological features of the area, which offer the opportunity to illustrate the stratigraphic, tectonic, and geomorphological framework of this sector of the Sicilian Chain within a relatively limited area.

On the other hand, the presence of urban settlements and associated infrastructure, while partially compromising the natural integrity of some sites, provides significant accommodation and food services. This enhances the usability of the geopath, including during off-peak tourist seasons. Furthermore, existing territorial constraints (Sites of Community Importance - SIC, nature reserves, and established geosites) have helped regulate urban expansion and recreational use of the area, allowing for the preservation of natural conditions despite the surrounding urbanization.

The proposed geopath, approximately 7 km in length, follows the jagged coastline of this Tyrrhenian sector of Sicily. The coastal morphology results from the differential erosion resistance of the exposed lithologies, which, combined with active tectonics, has produced a highly varied coastline. This includes high sea cliffs alternating with sandy and sandy-pebbly beaches, small coves, sea stacks, islets, and marine erosion platforms. The route enables observation of lithostratigraphic units ranging from the Upper Triassic to the Lower Pleistocene, with depositional facies transitioning from shallow marine (back-reef lagoon, tidal plain, neritic-coastal) to deep marine environments (escarpment to basin).

The selected sites have been quantitatively evaluated using the methods developed by Feuillet and Sourp (2011), and Vujičić *et al.* (2011). The potentially either scientific and touristic high value that the proposed geopath offers has been confirmed by the estimations which were performed according to two different approaches. In particular, according to Feuillet and Sourp (2011), over 70% of the selected sites possess high scores (above 5) in both the Management Rating (MR) and the Tourism Rating (TR). The results highlight the high scientific value and uniqueness of the majority of the proposed sites (excluding *Magaggiari* Beach, *La Praiola* Beach, and *Cala Rossa*, which are more commonly found in this coastal area). Additionally, the close proximity to the urban centers of Cinisi and Terrasini has resulted in high additional value scores, underscoring the excellent accessibility and usability of most sites. In fact, only 2 out of the 20 sites – those located within the airport perimeter – are effectively inaccessible, either directly or via observation points.

The remaining sites that are accessible by sea can currently be visited through private boat tours and guided excursions (e.g., *Grotta dei Nassi*), or indirectly through various vantage points along the coast. A complete view of the proposed geopath is available in the supplementary material (which features a perspective mainly from the sea and captured by drone).

The study confirms that the proposed geopath constitutes an outstanding outdoor educational laboratory, characterized by excellent accessibility and usability, particularly from land. To incorporate the less accessible sites into the itinerary, the authors suggest the institutionalization of sea-based services, to be managed by local associations (e.g., the *Capo Rama* Oriented Natural Reserve, local Pro-Loco organizations) or municipal authorities.

SUPPLEMENTARY MATERIAL

Other photos of the proposed geosites are available in Supplementary Material at https://doi.org/10.4454/mj45h78l

AUTHORS CONTRIBUTION

All authors contributed equally to the development of this work.

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