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From inventory and quantitative assessment of geosites to sustainable development: Case study of the Flyshs georoad of the Tangier Peninsula

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ABSTRACT

The Flyshs georoad runs from the western limit of the Jbel Moussa SIBE to southwest of Tangier presents different types of Flyshs. It located in the Rif (northern part of Morocco), which is characterized by metric to decametric thickness formations, generally representing alternating of sandstone beds and shale. A part of this area belongs to the Intercontinental Biosphere Reserve of the Mediterranean (RBIM). The Flyshs georoad hold a geodiversity that should be conserved since this type of rocks and climate of the study area favored the development of ecosystems. For this reason an inventory and quantitative assessment have been performed using the method of Brilha. As a result, twelve geosites have been selected, which represent the different units of the Flyshs and geological facies. Among the twelve geosites, ten of them have a scientific value (VS) over than 3.5. All geosites have a high educational and touristic value, due to their easy access and because they correspond to the Flyshs that are most representative in the Maghreb basin. However, the risk of degradation (DR) remains moderate. Geoconservation measures should be taken to protect the selected geosites. The Flyshs geotroad with the twelve geosites could help to ensure sustainable development and develop the geoeducation and geotourism in the study area.

Keywords: Flyshs, Tangier, inventory, geosite, georoad, quantitative assessment, scientific value.

INTRODUCTION

Geoconservation is gaining significant global attention, evidenced by the rising number of publications (e.g., Brilha, 2016; Lima, 2010; Reynard et al., 2016). Recognizing it importance, several works have focused on inventory and quantitative assessment, foundational steps in any geoconservation strategy (Wimbledon, 1996, Pereira & Brilha, 2010; Brilha, 2018…). It should be highlighted that many countries are actively developing such inventories: Porugal : Rocha et al., 2014; Spain: Fuertes-Gutiérrez & Fernández-Martínez, 2010; Fernández et al., 2014; France: Poiraud et al., 2016; Italy: Ferrando et al., 2021; Brazil: Reverte & Garcia, 2016; Mucivuna et al., 2017; Reverte et al., 2019. While some authors focuses on the base of the geoconservation strategy (inventory and quantitative assessment) which aim to conserve the geosites for the future generation, others deal with the use of geoheritage on geoeducation (Cayla et al., 2010; Bollati et al., 2011) as well as geotourism and geoparks (Hose, 2000; Newsome and Dowling, 2010; Štrba et al., 2018).

Moroccan territory holds an exceptional geodiversity, recognized at regional, national, and global scales, providing a valuable window into geological history. Recognizing the importance of preserving this geoheritage (e.g.; Tahiri et al., 2010a; El Hadi et al., 2015; Errami et al., 2013), Moroccan researchers have recently prioritized its study, with a particular focus on developing geosite inventories in diverse regions as a fundamental first step in implementing an effective geoconservation strategy: Rif area (Aoulad-Sidi-Mhend et al., 2019; Ben Ali et al., 2023); Meseta area (Mehdioui et al., 2020, 2022; Akhlidej et al., 2024); Middle Atlas area (Oukassou et al., 2019), Central Jbilet area (Kaid Rassou et al., 2019); Errachidia area (Si Mhamdi, 2023); Safi province (El hamidy et al., 2025). The inventory of geosites in the rif area (Northern part of Morocco) has been the focus of few works (Aoulad-Sidi-Mhend et al., 2019, 2020; Ben Ali et al., 2023). In addition to geodiversity, the study area also presents a unique space of its kind, in which the point where the Atlantic Ocean and the Mediterranean Sea meet contributes to the formation of special biological and ecological environments and favorably influences the fauna and flora and ecosystems. Moreover, part of the study area belongs to the Intercontinental Biosphere Reserve of the Mediterranean (RBIM) shared between Spain and Morocco and considered an important communication space between Africa and Europe, a strategic place with a remarkable natural heritage. It must be highlighted that the type of rocks and climate of the study area favored the development of ecosystems with rich in fauna (at least 175 taxa) and flora (Fennane and Ibn Tattou, 1988). This work aims to enrich the inventory in this part of Morocco in which a selection and quantitative assessment of geosites the Flyshs georoad of the Tangier Peninsula going to be done using the method of Brilha, 2016.

GEOGRAPHICAL AND GEOLOGICAL SETTING

The study area is located on the Strait of Gibraltar, in northern Morocco, precisely on the Tangier peninsula. It occupies a geostrategic position with two maritime façades overlooking the Atlantic and the Mediterranean. This area incorporates the coastline of the Fahs Anjra province and Tangier City, and includes the most important economic infrastructure in the Tangier-Tetouan-Alhoceima region (Tangier Med port). The expression ‘the Flysch georoad’ comes from the fact that this road allows the different types of Rifian flysch to be presented along an itinerary that starts at the western boundary of the Jbel Moussa SIBE at Douar Dchicha and ends at the famous Hercules cave to the south-west of the city of Tangier (Fig. 1). The Flyshs route is characterized by its varied geomorphological setting, with several exceptional cliffs, beaches, and islets. This often spectacular geomorphological heritage has excellent potential for promoting Earth sciences through tourism.

Geologically, the area belongs to the Rifain domain (Durand-Delga and Olivier, 1988; Esteras

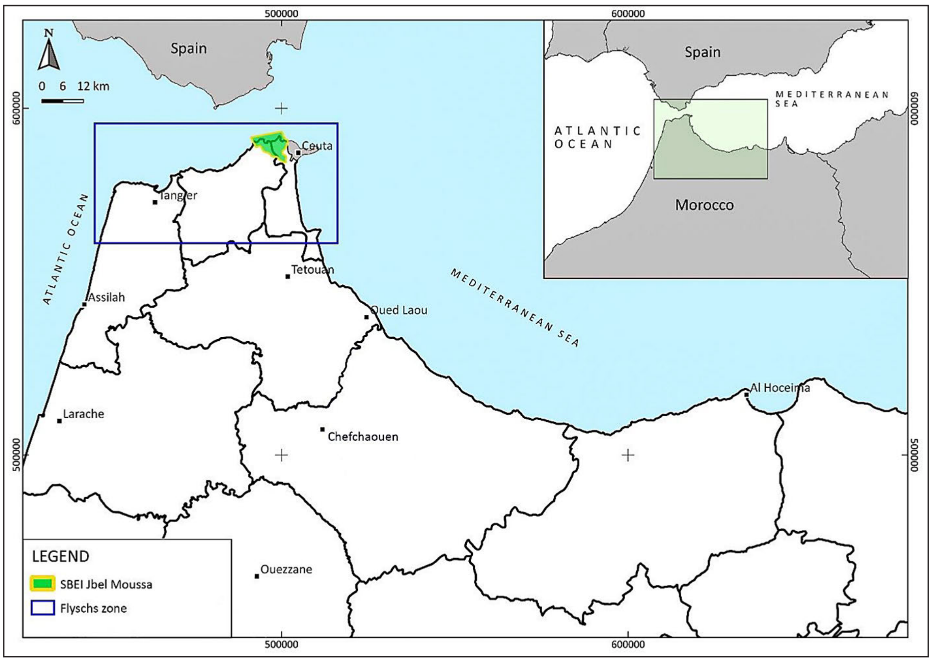

Figure 1. Geographical and administrative position of the flysch area

et al., 1995; Olivier et al., 1996; Durand-Delga et al., 1999; Guerrera et al., 2005). It is distinguished by the outcrop of three types of flysch that make up the Mediterranean coast of the peninsula and form the Maghreb flysch: the Mauretanian, the Massylian, and the Numidian (Figure 2).

The Maurétanian includes the Jbel Tisirène nappe and the Beni Ider nappe. The first consists of laminated mudstones with sandstone beds and micrite-claybeds from the Neocomian, followed by alternating fine-grained yellow sandstones and mottled mudstones (Andrieux, 1971; Durand Delga et al., 1999). The presence of Calpionella and Nannoflora in the Ras Cires section justify the age of terms from the Lower Berriasian to the Middle Albian. The sandstone input ceased a bruptly in the middle of the Albian, indicating a eustatic phenomenon during the first communication between the central and southern Atlantic (Delga et al., 1999).

The second consists of a detrital limestone-clay flysch with beds of greenish clay micrites and microbreccias from the Senonian, followed by limestones with *Microcodium* debris from the Palaeocene, red pelites, detrital biocalcarenites in slabs and conglomerates from the Lower-Middle Eocene, sandy to red silty pelites of the Upper Eocene-Oligocene, and alternating micaceous sandstones and pelites with flysch or molasse facies (sandstone-mica Oligocene) of the Terminal Oligocene-Aquitanian (Rahouti, 2004; Zaghloul et al., 2003). The Massylian includes the Melloussa and Chouamat nappes; it is referred to as 'Albo-Aptian flysch' as it consists almost exclusively of a turbiditics and stone-clay series of Albian and Aptianage (El Talibi et al., 2014).

The Numidian occupies a higher tectonic position and appears both on the other flyschs and on the external zones. At the base, it consists of sub-Numidian clays of Cretaceous ? - Paleogene age, on which depose a huge serie of quartz-sandstone bars alternating with pelites of Aquitanian-Burdigalian age. The supranumidianis made up of clays interspersed with levels of flint reaching Burdigalian age (Guerrera et al., 2012).

METHOD AND MATERIALS

The inventory and quantitative assessment of the Tangier peninsula Flysch geosites, required the use of a range of tools in order to ensure an effective selection and evaluation. An analytic study was undertaken, including: the literature review, the use of maps, and photos, the GPS coordinates during the field trips, discussions with the local community as well as the discussions with experts. The list of geosites made after the application of the qualitative criteria: representativeness, integrity, rarity and scientific knowledge (Brilha, 2016), then, they have been quantitatively assed using the 27 criteria proposed by Brilha (2016).

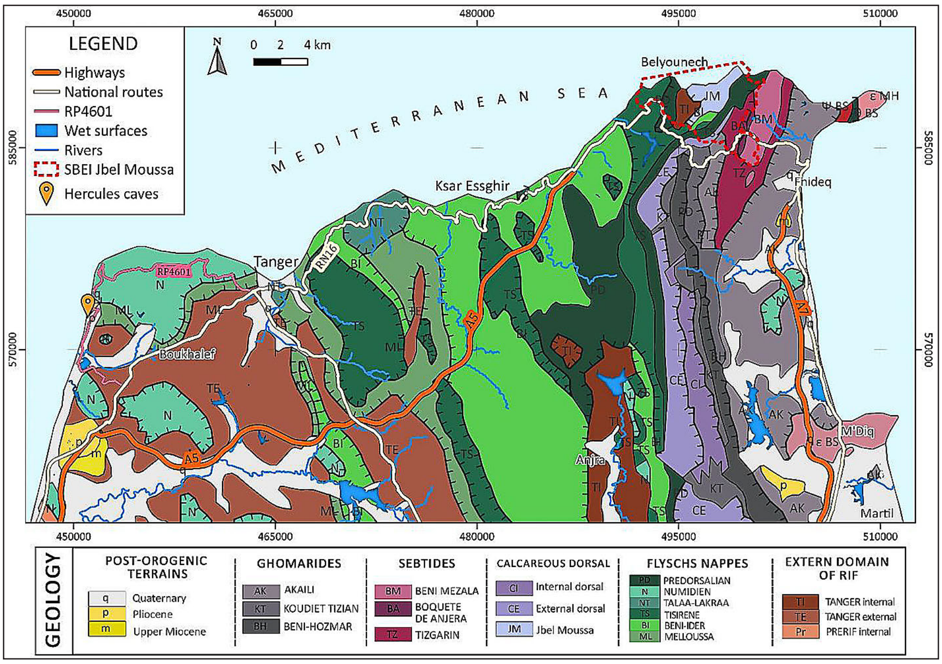

Figure 2. Geological setting of the Tangier Peninsula

7 criteria for scientific value, 10 shared between educationanl and touristic value, 2 specifically for educational value, 3 specifically for touristic value and 5 for degradation risk (Table 1) (Brilha, 2016). In addition, inventory sheets appropriate to the geosites in the study area have been carried out for more additional information (Aoulad-Sidi-Mhend et al., 2019; Benali et al., 2023; Mhend et al., 2023). The choice of the method of Brilha (2016) is come from the fact that it is building on previous works such as (Grandgirard, 1995; Bruschi and Cendrero, 2009; Pereira and Pereira, 2012). As well as, this method gives scientific value greater consideration than other types of values.

RESULTS

Inventory of the tangier Peninsula Geosites: from Douar Dchicha to Cap Spartel

The identification of geological sites representing the different flysch units and geological facies of the Tangier peninsula has led to identify twelve SGs based on their representativeness, rarity, and integrity. These flyschs are spread over the most accessible part of the peninsula and are the most visited by geologists and the general public interested in geomorphology and geology.

Geosite 1: The R'cham fold and surrounding panorama (Hafat Banat, Oued Rmel dam)

This geosite exposes the tectonic deformations that took place between the inner zone and the flysh which are the result of the stresses leading to the surrection of the Rifaine chain. The geosite is located on the N16 road, where the large Mauritanian turbiditic bars of the Jbel Tizirène unit (Neocomian Albian of the Lower Cretaceous) could be seen, representing multi-centred anticlinal structures with large radii of curvature of generally parallel submeridian axes, in the form of open chevrons (inter-flank angles 60° on average), asymmetrical, straight and dipping to the west (Mrihi, 2005) (Fig. 3).

Not far from Douar Dchicha, the R'cham anticline (Fig. 3A) forms a decametric to hectometric knee fold with axes N165, 30°E and an axial plane N00, 70E. The long flank is at S0 N10, 40E, the short flank is at S0 N165, 65E.

The great R'cham fold maintains a simple anticlinal structure deflected westwards at the level of the large sandstone beds, whereas, in the fine geopolitical levels of the western flank, the folding becomes very tight and gives metric folds (Fig. 2a). These are over thrusting folds associated with flat dipping thrusts to the west.

Table 1. The criteria of scientific value, educational use potential, and risk of degradation, their scores and weights

Values	Criteria (Brilha, 2016)	Weight (%)
Scientific value (SV)	Representativity (Rpt)	30
	Integrity (Int)	15
	Rarity (Rar)	15
	Key locality (KL)	20
	Scientific knowledge (SK)	5
	Geological diversity (GD)	5
	Use limitations (UL)	10
Potential for educational use (PEU)	Vulnerability (Vul)	10
	Accessibility (Acc)	10
	Use limitations (UL)	5
	Safety (Saf)	10
	Logistics (Log)	5
	Density of population (DP)	5
	Association with other values (Av)	5
	Scenery (Sce)	5
	Uniqueness (Uni)	5
	Observation conditions (OC)	10
	Didactic potential (DP)	20
	Geological diversity (GD)	10
Potential Touristic use (PTU)	Vulnerability (Vul)	10
	Accessibility (Acc)	10
	Use limitations (UL)	05
	Safety (Saf)	10
	Logistics (Log)	05
	Density of population (DP)	05
	Association withother values (Av)	05
	Scenery (Sce)	15
	Uniqueness (Uni)	10
	Observation conditions (OC)	05
	Interpretation potential (IP)	10
	Economic level (EL)	05
	Proximity of recreational areas (RA)	05
Degradation risk (DR)	Deterioration of geological elements (Dg)	35
	Proximity to areas/activities with potential to cause degradation (PD)	20
	Legal protection (LP)	20
	Accessibility (Acc)	15
	Density of population (DP)	10

The massive white limestones of the Hafat El Banat scale of the Sinemurian age can also be seen to the south from this large fold. Below this formation, which belongs to the Internal Dorsal, are quarries that exploit carbonate rocks, especially the grey Dolomites and the massive Héttangian.

Heading north, the stop-off offers an opportunity to observe a dam whose embankment is built between two hard formations of the Tizirène. The dam has been built on Oued Rmel (a small river flowing into the sea) (Fig. 3b) since 2006 and was inaugurated in May 2008; the purpose of its construction is to supply water to the port complex and its surroundings; its reservoir has a surface area of 123 hectares and a capacity of 23 million m^3. The dam's location offers a panoramic view of the Punta Cires Klippe and the logistics infrastructure of the Port of Tangier-Med.

Geosite 2: The flute casts of Punta Cires

As you take the N16 road towards Port-Med and descend towards the Dalia coast, you come across a thick, highly deformed series of sandstone and sandstone-pelite turbidites of Lower Cretaceous age (Durant-Delga 1998; Durant-Delga et al., 1999) (Fig. 4). The series belongs to the vast flap of the Mauritanian Jbel Tisirène nappe and forms the lower part of the Maghreb Flyshs. It occurs at Punta Cires, in a normal position dipping west wards at 30 to 45° (Kornprobst and Durand-Delga 1985; Chalouan et al., 2006, 2011) (Fig. 4a).

At the base of this sandstone series (north-facing slope), flute-cast type sedimentary features outcrop on the lower face of the banks; they were formed as a result of marine erosion (Fig. 4b). This type of figure is formed by the scouring of the bottom by marine currents (vortexes); it can be recognized by its elongated or triangular shape, the 'tail' of which indicates the direction of the current. Flute casts are indicators of the action of paleocurrents identified at the base of turbidites and also in certain river channels.

On the N16 road, opposite the mosque and on the southern slope of Punta Cires, an alternation of marly-calcareous and sandstone turbidites can be seen, affected by folds, and dated by nannoflora to the Middle-Upper Hauterivian (preflyshs) (Chalouan et al., 2006, 2011) (Fig. 4C).

Geosite 3: Current patterns and inverted series of the Tizirène nappe at Ksar Sghir

On the cape of Ksar Sghir, heading towards Tangier and beyond the big bend to the west, located the inverted series of the Tisirène nappe (GPS: 35°50'56''N; 05°33'59''W). The Lower

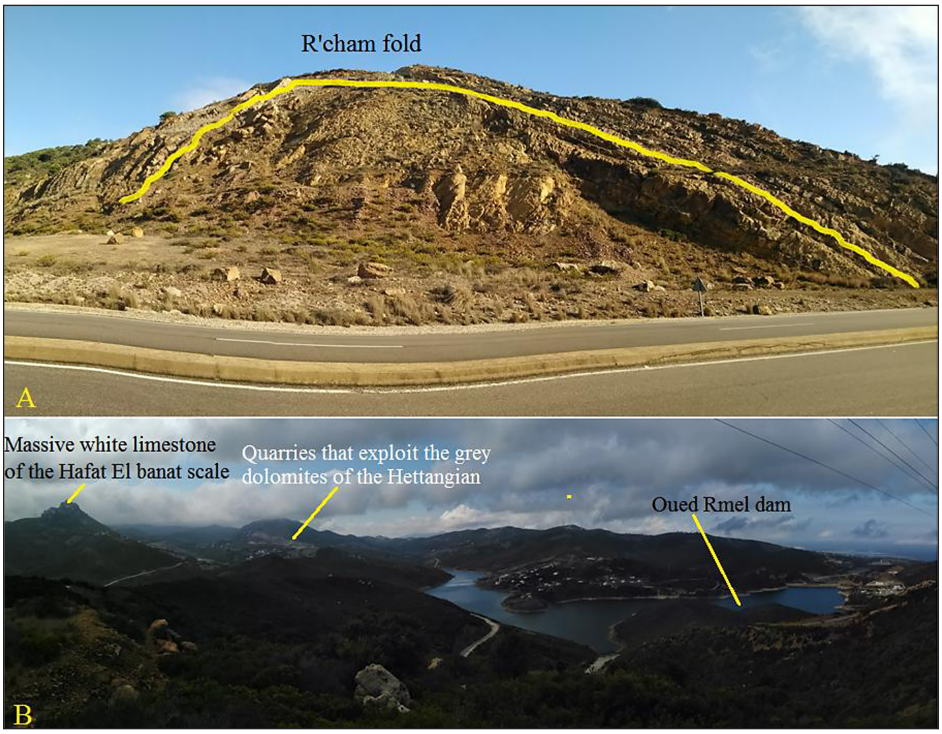

Figure 3. The R'cham fold and neighboring panorama, A. The R'cham fold, B. The Hafat El Banat limestone massif, the exploitation of Hettangian grey dolomites, and the Oued Rmel dam

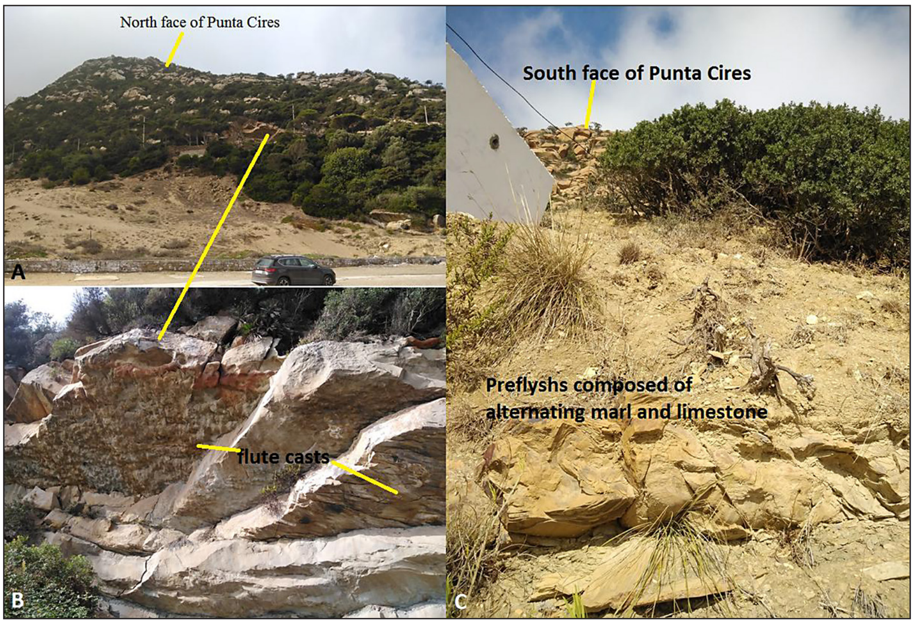

Figure 4. Sedimentary features at the base of Punta Cires and the preflyschs

Cretaceous sandstones of the Tisirène nappe dip 60–70° to the NW in an anomalous position (Fig. 5). The Tisirène flysch forms an overlapping flap with the Beni Ider flysch, which in turn reveals the extent of internal deformation of the flysch nappes, with a vergence towards the west. This is the tectonics of the accretionary prism at the front of the Alboran arc, first in compression, then in extension. In addition to its structural interest, the geosite have also a sedimentological interest. The anomalous position of the sandstones means that the bases of the banks, which are well exposed, reveal 'flute casts' (Fig. 5a) and 'groove casts'. Crescent marks are created when an object placed on the bed causes a deflection of the current lines. It is results of erosion in front of the object and deposition behind it. The shape of the pattern is controlled by the geometry of the object. This pattern is very common in coastal environments.

Besides the scientific value, the Ksar Sghir geosite have also a cultural value since it consider as a witness of medieval civilization (Elbl, 2004). It covers an area of around 2.5 hectares and comprises two monumental and urban units: the Islamic town and the Portuguese citadel (Fig. 5b). The Islamic town is set within a circular enclosure 200 m in diameter, giving it a unique planimetric and urban character, both in Morocco and in the Muslim West. This small town in the north of Morocco, ten kilometers from the port of Tangier-Med, is an essential stop-off point for Moroccans living abroad on their way to / or from Europe. The medieval occupation of the site was preceded by a documented human presence in its immediate vicinity, dating back to antiquity and even prehistoric times.

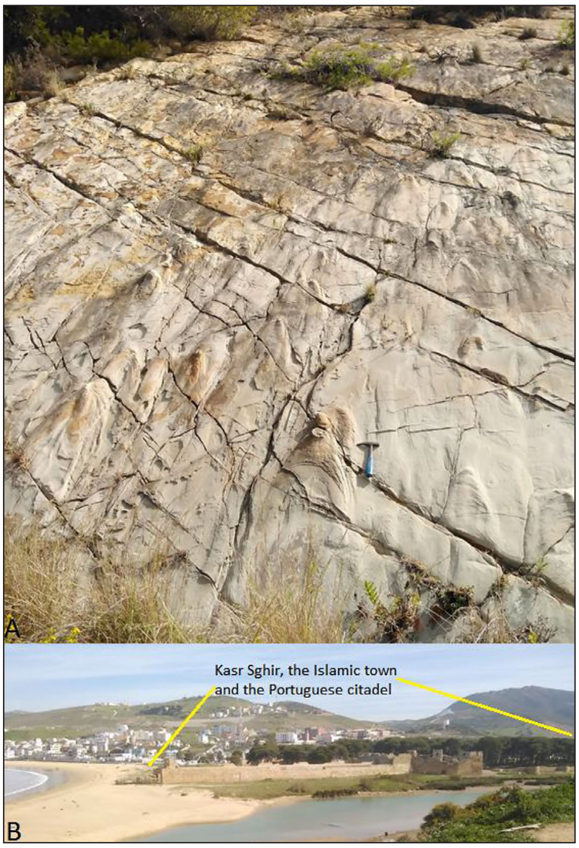

Figure 5. Sedimentary figures at the base of the Tisirene turbidites at Kasr Sghir; (a) Crescent-shaped figures, (b) Kasr Sghir

Geosite 4: The sandstone-mica flysch of the Oued Ledian coast

Continuing along the road as far as the Oued Ledian coast on the right bank of the Oued Ledian River, we can observe the Lower Oligocene-Burdigalian sandstone-mica flysch of the Beni Ider nappe. The series is deformed, with open NW-SE folds in which the beds are almost vertical (Fig. 6). These sandstone beds are interspersed with pelites. The bands that make up the Bouma sequence can be found. The activity of marine waters has left erosive traces by sculpting the soft sandstone-pelite series of the Oued Ledian coast.

Geosite 5: Talaat Lakraa mixed flysch

This geosite has an exceptional type of flysch, belonging to the Talaat Lakraa nappe which overcomes both the Melloussa nappe and the Béni Ider nappe. This nappe is characterized by facies intermediate between those of the Beni Ider and Numidian nappes. It is assumed that it corresponds to a part of the Oligo-Miocene basin intermediate between the northern part (deposition of the Beni Ider flysch, dependent on contributions from the Alboran domain) and the southern part (deposition of the Numidian sandstones, dependent on African contributions) (Fig. 7a) (Chalouan et al., 2011).

The geosite allows us to see a succession of yellow clayey-calcareous Flysch material with detrital banks rich in rounded white quartz (long transport) and limpid and other blunt grey quartz of the Senomian-Paleocene. These formations in contact with the sea are a particular geomorphological feature of the Hjar Sfar geosite, where the yellow sandstone rocks are sculpted naturally, giving the coastline a spectacular attraction (Fig. 7b). Playa Blanca, a small beach is a geomorphological unit offering a beautiful bathing landscape characterized by its fine white sands (Fig. 7c), some of whose constituents are of organic origin. This is the case of the white sand of the atolls, composed of fragments of coral, shells, and skeletons of organisms.

Geosite 6: Beni Ider of Sidi Kankouch

At Beni Ider of Sidi Kankouch, the Lower Eocene components of the Beni Ider Flysch (Zaghloul et al., 2002) can be seen almost vertically (Fig. 8a). The succession of soft layers consists (Fig. 8b) of red and hard pelites, detrital biocalcarenites in slabs and Ouljien marine conglomerates (Gharbaoui, 1981). Its position in contact with the sea gives it an attractive geomorphology to nature lovers. These turbidites are affected by synsedimentary folding (Fig. 8c). The geosite is crossed by two small streams: Sidi Kankouch 1 and 2, separated by a hill where the Marabot of Sidi Kankouch is located. The geosite offers to students the opportunity to observe the sedimentation characteristics of the seabed and the Bouma series (Fig. 8d).

Figure 6. The sandstone-mica flysch of the Oued Ledian coast

Figure 7. Mixed flysch; (a) Oligomiocene sandstones of the Talaa Lakraa nappe; (b) result of the erosive activity of marine waters; (c) the landscape of Hjar Sfar beach

Geosite 7: Cap Malabata

The Cap Malabata geosite offers the chance to see the Oligocene constituents of the Beni Ider Flysch installed in a normal position. The emergence of a matorral-type forest gives the cape a strategic position that is remarkable for the authorities, who chose to build an 18 m high minaret with a gallery and lantern (Fig. 9a). The cape closes to the Bay of Tangier, from the Strait

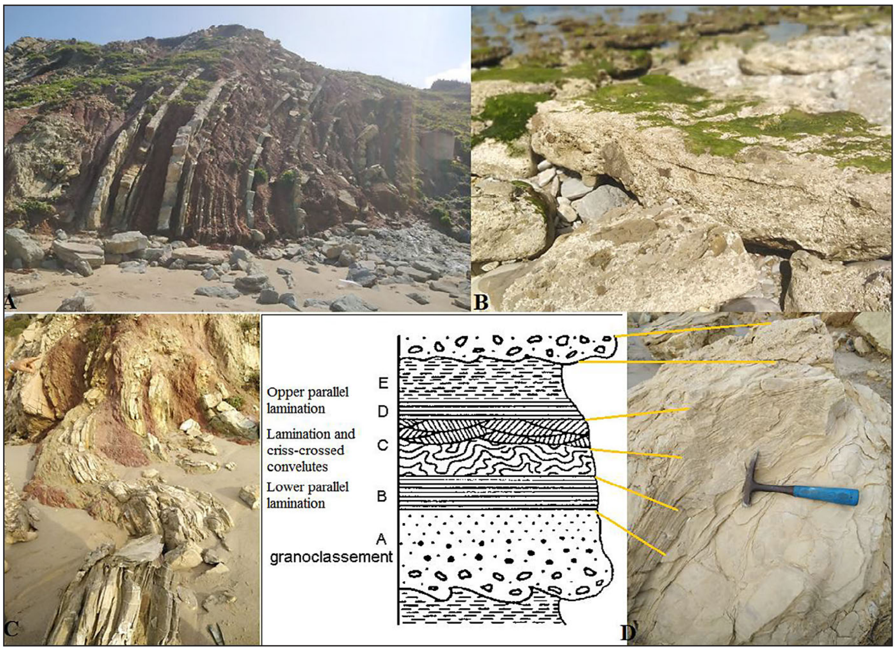

Figure 8. The Beni Ider of Sidi Kankouch, (a) Lower Eocene of the Beni Ider Flysch, (b) Ouljien marine conglomerates, (c) turbidites affected by synsedimentary folding; (d) Bouma series

Figure 9. Cape Malabata, (a) Malabata minaret and the Oligocene Flysch of Beni Ider, (b) Tangier Bay, (c) Italian castle

of Gibraltar could be seen (Fig. 9b). Tangier Bay located between 35° 46‘ and 35° 48’ N and 5° 45‘ and 5° 49’ W. It represents the maritime part of a depression carved out between two rocky points that open onto the Strait of Gibraltar (Fig. 10): “Cap Malabata” and “Pointe des Juifs”. The geology of these two points is characterized by the exposure of two layers of flysch, the Béni-Ider and the Numidian (Humbert, 1971; Didon et al., 1984; Hoyez, 1989; Achab et al., 2005).

Geosite 8: The Upper Cretaceous of the Beni Ider nappe and the Italian Castle

Towards the east of the cape, a building on a hill attracts the attention of all passengers: the Italian Castle (Fig. 10c). It was built at the beginning of the 20th century on a 10-hectare site on a hill characterized by the formation of turbidites. This geosite offers an opportunity to observe the Cenomanian-Turonian slabs of flint limestone, folded and affected by the Alpine orogeny. Red clays can also be seen in the vicinity of the hill.

Geosite 9: Phoenician Necropolises and the Numidian

The geosite is of geocultural interest, corresponding to a necropolis where man excavated sandstone rock to bury the dead (Fig. 11a). This (fragile) rock belongs to the Numidian sandstones (Durand-Delga and Mattauer, 1959b; Didon et al., 1984). Human activity dates back to the Punic-Roman period and is one of the only ancient remains in Tangier. There are 88 burials, dug between the 4th and 1st centuries BC. Some are grouped in pairs, probably reserved for couples.

The Phoenician necropolises of Tangier can be reached on foot from the mythical Café Hafa, which overlooks the Bay of Tangier and provides a vantage point for observing the southern part of the Arch of Gibraltar (Fig. 11b). Although the mythical café is an integral part of the city’s heritage, the necropolises constitute another heritage, overlooking the Alboran Sea, making this a place of multidisciplinary interest.

Geosite 10: The Numidian of Cap Spartel

The Numidian is the dominant facies at Cape Spartel (Fig. 11a) and the surrounding area. It is a flysch nappe of the Rifain domain (Durand-Delga and Mattauer, 1959) forming a sandstone relief thrust onto the Tangier unit and the Meloussa nappe (Fig. 10). It takes the form of an elongated klippe to the north-west. Generally speaking, it begins with sub-Numidian argillites (Raoult, 1974; Didon, 1964) which are surmounted by an azoic sandstone massif over 1000 m (Vila, 1980), probably of terminal Oligocene or even lower Miocene age. This allochthonous nappe is affected by late tectonic faults. The Cape Spartel Numidianis an uninverted series, vulnerable to erosion (Fig. 12b) and affected by a northwest/southeast anticline. Wadi Ihoud is adapted to another south-north fault which exposes the full thickness (300–400 m) of the sub-Numidian clays (El Gharbaoui, 1981).

The geosite at stop 11 is the famous Cap Spartel, which is much visited by tourists (Fig. 12a). Near Cap Spartelis the diplomatic forest of biological and ecological interest, at downstream the rocky coasts of Bouhindia, Achakkar, and the place where the Atlantic Ocean meets the Alboran Sea could be found. Not far away is the Grotte d’Hercule, an exceptional tourist attraction on the Tangier peninsula. The Cap Spartel light house was built by order of Sultan Mohamed ben

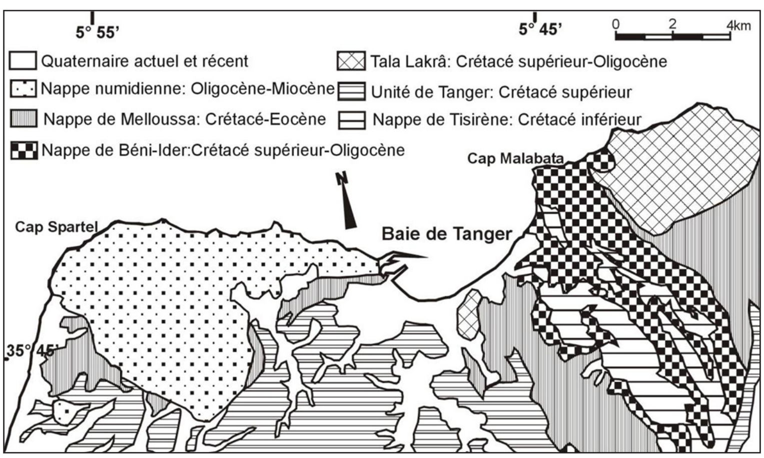

Figure 10. Geological map of the Tangier Flysch (SECEG/SNED 1990, Achab et al., 2005, modified)

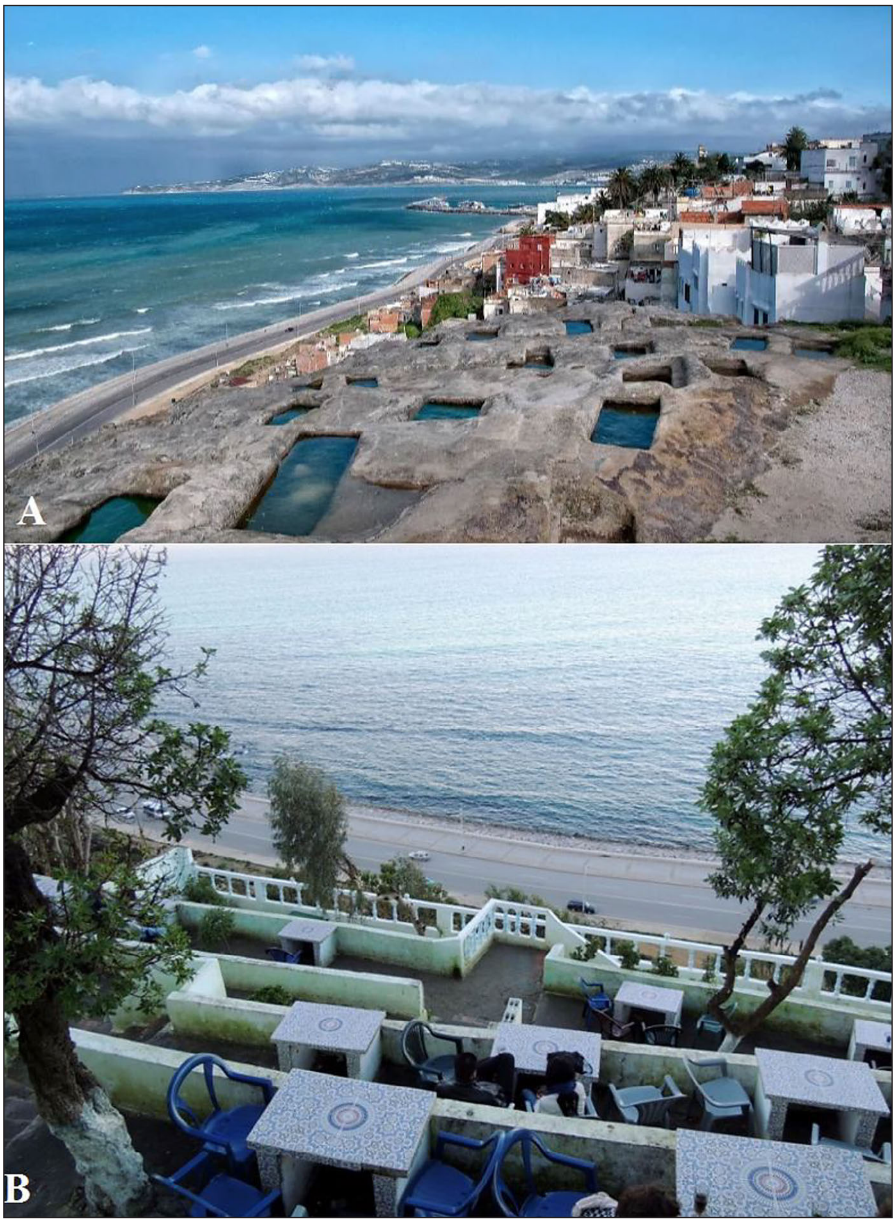

Figure 11. Phoenician necropolises and the Numidian, A. The Numidian of Tangier houses the Phoenician necropolis, B. The famous café of Hafa was built on the Numidian

Abderrahmane in 1861 under the supervision of French architect Léonce Reynaud. Its architecture was inspired by a Hispano-Moorishmosque. The light house is in the shape of a minaret, 31 meters high, and played a very important role in navigation at the time. The decision-makers have built roads to facilitate access (Fig. 12c) to the Numidian sandstone outcrops due to the heritage potential and the flow of visitors.

Geosite 11: Achakar calcarenites

The geosite is located 3 km southwest of Cap Spartel, at the mouth of the Oued Achakar (Fig. 13A), also known as Oued Zaitoun, which has a low flow rate. The mouth is dominated by 20 m-high carbonate cliffs (Fig. 13a, b) and contains bioclasts, sand grains, and gravels. A succession of facies can be distinguished: (i) Gravel-rich bioclastic limestone, massive at the base and organized in thick banks; (ii) Sandy marl with intercalation of bioclastic limestone levels; (iii) A 0.5 m-thick layer of fine limestone (Alouane 1996). These rocks have been exploited since antiquity and the Middle Ages, and have been used up to the present day for the extraction of hard materials (millstones).

The Achakar calcarenites are vulnerable to water erosion, a process that has carved out caves

Figure 12. The Numidian and Cape Spartel, (a) the minaret at Cape Spartel, (b) Numidian sandstone susceptible to erosion, (c) infrastructure enhancing the Numidian rocks

Figure 13. Achakar calcarenites, (a) Achakar river calcarenites, (b) El Khil caves

and grottoes known as the Grottes El Khil or El Khail (Fig. 13B) (Souville, 1984; Messili, 2005).

Excavations of the El-Khil B and C caves have yielded assemblages that enable us to revise the chronology of Achakar-type ceramics. The study also highlights two traditions in northern Morocco during the Middle Neolithic. The first stems from the tradition of printed ceramics and is rooted in the Cardial Neolithic known throughout the Mediterranean world (Martínez Sánchez et al., 2018).

Geosite 12: Grotte Hercule

Grotte d'Hercule (Fig. 14a) is located 100 m from Oued Achakar, to the south-west of Tangier. The cave was officially opened in 1920 and declared a national heritage site by the Ministry of Culture in 1950. The nature of the rock is calcarenite, where a cave linked to the myth of Hercules was dug. The cave was once known for its use as a grinding stone, and traces of this activity can be seen in Figure 14B. It is visited by tourist to discover its geocultural interest (Fig. 14C). The visit used to be free, but since June 2024 it has become chargeable; ticket prices are 30 dirhams for nationals and 60 dirhams for foreign visitors.

QUANTITATIVE ASSESSMENT OF THE TANGIER PENINSULA GEOSITES

After a detailed qualitative description of the georoad, a quantitative assessment has been performed using the Brilha (2016) method. For a more suitable characterization, an inventory sheets appropriate to the geosites have been drawn in the study area (Aoulad-Sidi-Mhend et al., 2019; Benali et al., 2023; Mhend et al., 2023).

Scientific value (SV)

The results of the scientific value and the averages of these criteria are summarized above, in Table 2. Diversity is expressed by the presence of five types of SGs: structural, hydrogeological, geomorphological, sedimentological, and geocultural. Their characteristics testify to the internal geodynamic processes responsible for the evolution of the rifaine (alpine) chain about plate tectonics. The characteristics of certain SGs are related to water erosion and anthropic action.

The SGs of the Flysch georoad have a high scientific value, with scores higher than of 3.5, due to the high level of geodiversity. This value is the result of the following facts:

Figure 14. Hercules cave, (a) opening to the Atlantic, (b) traces of calcarenite mining for grinding stones, (c) inside the Hercules cave and tourist facilities

Table 2. Typology and assessment of scientific value criteria of the studied GSs and their weighted average

N°	Nom de SGs	Typologie	Rpt	LC	CS	Int	DG	Rar	RU	SV
1	R'chamfold and surrounding panorama	Structural	1.2	0.4	0.2	0.6	0.2	0.6	0.4	**3.6**
2	flutecasts of Punta Cires	Sedimentology	1.2	0.4	0.2	0.6	0.2	0.6	0.4	**3.6**
3	Current patterns and invertedseries of the Tizirène nappe at Ksar Sghir	Structural	1.2	0.4	0.2	0.6	0.2	0.6	0.4	**3.6**
4	The sandstone-mica flysch of the Oued Lediancoast	Sedimentology	1.2	0.4	0.2	0.6	0.2	0.6	0.4	**3.6**
5	Talâat Lakraa	Sedimentology	1.2	0.4	0.2	0.6	0.1	0.6	0.4	**3.5**
6	Bl de Sidi Kankouch	Sedimentology	1.2	0.4	0.2	0.6	0.2	0.6	0.4	**3.6**
7	Italian Castle	Geocultural	1.2	0.4	0.2	0.6	0.2	0.6	0.4	**3.6**
8	Cap Mnar	Geomorphology	1.2	0.4	0.2	0.6	0.2	0.4	0.4	**3.4**
9	Phoenician and Numidiannecropolises	Geocultural	1.2	0.4	0.2	0.6	0.2	0.6	0.4	**3.6**
10	Numidian of Cap Spartel	Sedimentology	1.2	0.4	0.2	0.6	0.2	0.6	0.4	**3.6**
11	Achakarcalcarenites	Geocultural	1.2	0.4	0.2	0.6	0.2	0.6	0.4	**3.6**
12	Grotte Hercule	Geocultural	1.2	0.4	0.2	0.6	0.2	0.6	0.4	**3.6**
Weighted average			1.20	0.40	0.20	0.60	0.19	0.58	0.38	**3.55**
Weight			30%	20%	15%	15%	5%	5%	10%	100%

Note: *representativity (Rpt), integrity (Int), rarity (Rar), key locality (KL), scientific knowledge (SK), geological diversity (GD), use limitations(UL), scientific value (SV).

1) Geosites are well preserved and visible to the naked eye, resulting in a very high score.
2) The ability of SGs to illustrate geological processes and structures in the study area.
3) The importance of these SGs as references or explanatory models of facts related to geological processes.
4) The numerous scientific studies published on the metamorphism of the study area, which hosts geosites whose results reflect their VS.

Potential educational utility (PEU) value

The PEU value reflects the relationships and effects of the external environment, natural and/or cultural aspects, on the SGs. It assesses the conditions of observation by students and the resistance of SGs to possible degradation by visitors (vulnerability). It also highlights the state of infrastructures (accessibility, accommodation, catering, communication network and security). All the values of these criteria are summarized in the PUE evaluation table, along with their weighted average (Table 3). Based on the discussion of the criteria for the value of the potential for educational use and the calculation of the average, which is around 3.72, we conclude that the educational value is very high. Most of the SGs are located close to paved roads (with no restrictions on use) and are easily accessible by all means of transport. In addition to their association with sites of ecological and/or cultural interest, which gives additional value to SGs, they are recognized for their resistance to degradation by visitors. The value of the PUE is kept very high by the fact that the geosites are observable and in a good state of conservation.

The touristic potential (PTU) value

The touristic value shows the relationships and influence of the external environment, i.e. natural and/or cultural appearances on geosites. It assesses the conditions under which the general public can observe nature and the geosites resistance to possible destruction by visitors (vulnerability). It also highlights the state of infrastructures (accessibility, accommodation, catering, communication network and security). The values of these criteria are summarized in the table below (Table 4).

The criteria for the PTU value and the calculation of the average PTU of the SGs, which is around 3.64, lead to the conclusion that the PTU value is very high. This value is explained by the proximity of most of the geosites to paved roads, the existence of major tourist infrastructure, and the association of the SGs with sites of exceptional biological and/or cultural interest. The opening of new transport links (TGV and port-Med) has made the Tangier Flysch georoad more accessible, and there are no restrictions on use in almost all the SGs in the area.

Table 3. Quantitative Assessment of educational value criteria and their weighted average

N°	Nom de SIGeo	Vul	Acc	RU	Séc	Log	DP	AV	Pay	Uni	CO	PD	DG	EUP
1	R'chamfold and surrounding panorama	0.4	0.4	0.2	0.3	0.2	0.15	0.2	0.2	0.1	0.3	0.8	0.4	**3.7**
2	flutecasts of Punta Cires	0.4	0.4	0.2	0.3	0.2	0.15	0.2	0.2	0.1	0.3	0.8	0.4	**3.7**
3	Current patterns and invertedseries of the Tizirène nappe at Ksar Sghir	0.4	0.4	0.2	0.3	0.2	0.15	0.2	0.2	0.1	0.4	0.8	0.4	**3.8**
4	The sandstone-mica flysch of the Oued Lediancoast	0.4	0.4	0.2	0.3	0.2	0.15	0.2	0.2	0.1	0.4	0.8	0.4	**3.8**
5	TalâatLakraa	0.4	0.4	0.2	0.3	0.2	0.15	0.2	0.2	0.1	0.4	0.8	0.3	**3.7**
6	BI de Sidi Kankouch	0.4	0.4	0.2	0.3	0.2	0.15	0.2	0.2	0.1	0.4	0.8	0.4	**3.8**
7	Italian Castle	0.4	0.4	0.2	0.3	0.2	0.15	0.2	0.2	0.1	0.4	0.8	0.4	**3.8**
8	Cap Mnar	0.4	0.4	0.2	0.3	0.2	0.15	0.2	0.2	0.1	0.4	0.8	0.4	**3.8**
9	Phoenician and Numidiannecropolises	0.4	0.4	0.2	0.3	0.2	0.15	0.2	0.2	0.1	0.4	0.8	0.4	**3.8**
10	Numidian of Cap Spartel	0.4	0.4	0.2	0.3	0.2	0.15	0.2	0.2	0.1	0.4	0.8	0.4	**3.8**
11	Achakarcalcarenites	0.4	0.4	0.2	0.3	0.2	0.15	0.2	0.2	0.1	0.4	0.8	0.4	**3.8**
12	Grotte Hercule	0.4	0.4	0.2	0.3	0.2	0.15	0.2	0.2	0.1	0.4	0.8	0.4	**3.8**
Weighted average		0.40	0.40	0.20	0.30	0.20	**0.15**	0.20	0.20	0.10	0.38	0.80	0.39	**3.72**
Weight		10%	10%	5%	10%	5%	5%	5%	5%	5%	10%	20%	10%	100%

Note: * vulnerability (Vul), accessibility (Acc); use limitations (UL), safety (Saf), logistics (Log), density of population (DP), association with other values (Av), scenery (Sce), uniqueness (Uni), observation conditions (OC), didactic potential (DP), geological diversity (GD), educational use potential (EUP).

Table 4. Quantitative assessment of touristic value criteria and their weighted average

N°	Nom de SGs	Vul	Acc	UL	Saf	Log	DP	AV	Sce	Uni	OC	IP	EL	RA	TUP
1	R'chamfold and surrounding panorama	0.4	0.4	0.2	0.3	0.2	0.2	0.2	0.6	0.2	0.15	0.4	0.2	0.2	**3.6**
2	Flutecasts of Punta Cires	0.4	0.4	0.2	0.3	0.2	0.2	0.2	0.6	0.2	0.15	0.4	0.2	0.2	**3.6**
3	Current patterns and invertedseries of the Tizirène nappe at Ksar Sghir	0.4	0.4	0.2	0.3	0.2	0.2	0.2	0.6	0.2	0.20	0.4	0.2	0.2	**3.7**
4	The sandstone-mica flysch of the Oued Lediancoast	0.4	0.4	0.2	0.3	0.2	0.2	0.2	0.6	0.2	0.20	0.4	0.2	0.2	**3.7**
5	TalâatLakraa	0.4	0.4	0.2	0.3	0.2	0.2	0.2	0.6	0.2	0.20	0.4	0.2	0.2	**3.7**
6	BI de Sidi Kankouch	0.4	0.4	0.2	0.3	0.2	0.2	0.2	0.6	0.2	0.20	0.4	0.2	0.2	**3.7**
7	Italian Castle	0.4	0.4	0.2	0.3	0.2	0.2	0.2	0.6	0.2	0.20	0.4	0.2	0.2	**3.7**
8	Cap Mnar	0.4	0.4	0.2	0.3	0.2	0.2	0.2	0.6	0.2	0.20	0.4	0.2	0.2	**3.7**
9	Phoenician and Numidiannecropolises	0.4	0.4	0.2	0.3	0.2	0.2	0.2	0.6	0.2	0.20	0.4	0.2	0.2	**3.7**
10	Numidian of cap spartel	0.4	0.4	0.2	0.3	0.2	0.2	0.2	0.6	0.2	0.20	0.4	0.2	0.2	**3.7**
11	Achakarcalcarenites	0.4	0.4	0.2	0.3	0.2	0.2	0.2	0.6	0.2	0.20	0.4	0.2	0.2	**3.7**
12	Grotte Hercule	0.4	0.4	0.2	0.3	0.2	0.2	0.2	0.6	0.2	0.20	0.4	0.2	0.2	**3.7**
Weighted average		0.40	0.40	0.20	0.30	0.20	0.15	0.20	0.60	0.20	0.19	0.40	0.20	0.20	3.64
Weight		10%	10%	5%	10%	5%	5%	5%	15%	10%	05%	10%	05%	05%	100%

Note: * vulnerability (Vul), accessibility (Acc), use limitations (UL), safety (Saf), logistics (Log), density of population (DP), association with other values (Av), scenery (Sce), uniqueness (Uni), observation conditions (OC), interpretation potential (IP), economic level (EL), proximity of recreational areas (RA), touristic use potential (TUP).

Degradation risk value

Degradation risk (DR) assessment is based on five criteria. Its importance come from the fact that geological features have a high probability of being damaged by anthropogenic or natural factors when the geosite is not protected by legal laws and when it is close to natural hazard zones and potentially degrading activities. Table 5 the degradation risk values, the 5 criteria, and the weighted averages for each of the Flysch georoad SGs.

The average degradation risk of the SGs studied is moderate, around 2.8. We note that all these SGs have a moderate risk of degradation (Tab. 5) because the main features of the geological elements are likely to be damaged by anthropogenic or natural factors, as a result of uncontrolled access. This factor is compounded by the proximity of most of the geosites in the study area to roads and unexpected land developments (Tab. 5).

DISCUSSION

The study of geodiversity along the Tangier peninsula, in particular the Flysh georoad sector, allowed us to identify twelve (12) geosites. Inventory and quantitative assessment of the Tangier peninsula geosites using the method of Brilha 2016 indicate high scientific, educational and touristic value, and a moderate risk of degradation of all geosites.

The moderate RD values obtained for the SGs are an incentive to take geoconservation measures, which involve conservation of geoheritage for the future generation, as well as the development of geotourism and geoeducation action plan to enhance the sustainable development in this area. Moreover, all stakeholders (local-regional authorities, local population, scientists, NGOs, etc.) need to be involved in implementing the protection of the geological heritage of the Tangier and Fahs Anjra commune. This protection requires strict laws enforced by the authorities to enhance and preserve those geosites (Fig. 15), which have all the characteristics to develop geoeducation in a georoad with different themes: (i) regional geology in its relationship with internal geodynamics responsible for the structural evolution of the Rif mountain range, (ii) external geology illustrating the action of water on carbonate rocks, and Karst, (iii) landscape structuring in the Tangier peninsula where Man has enhanced his natural surroundings.

Acknowledging the significant geological resources of the Tangier peninsula, in combination with its distinctive human heritage, it is strongly recommended to implement a geopark project to preserve geological heritage, foster geotourism, and stimulate regional economic development. This georoad accessible and has the infrastructure to be used as an educational and tourist road. The characteristics of this georoad, as traced, are presented in the following table (Table 6).

The use of the 12 geosites on geotourism and geoeducation aims to improve methods of acquiring knowledge in the field of earth science and to materialize geological facts for students and/or teachers by moving from theoretical knowledge to practical observations. In addition, the Flyshs Georoad is also proposed to geotourism enthusiasts; it could motivate visitors to appreciate the

Table 5. Assessment of degradation risk value criteria of the studied GSs and their weighted average

N°	Nom de SG	Dg	PD	LP	Acc	DP	DR
1	R'chamfold and surrounding panorama	0.7	0.8	0.4	0.6	0.3	2.8
2	Flutecasts of Punta Cires	0.7	0.8	0.4	0.6	0.3	2.8
3	Current patterns and invertedseries of the Tizirène nappe at Ksar Sghir	0.7	0.8	0.4	0.6	0.3	2.8
4	The sandstone-mica flysch of the Oued Lediancoast.	0.7	0.8	0.4	0.6	0.3	2.8
5	Talâat Lakraa	0.7	0.8	0.4	0.6	0.3	2.8
6	BI de Sidi Kankouch	0.7	0.8	0.4	0.6	0.3	2.8
7	Italian Castle	0.7	0.8	0.4	0.6	0.3	2.8
8	Cap Mnar	0.7	0.8	0.4	0.6	0.3	2.8
9	Phoenician and Numidiannecropolises	0.7	0.8	0.4	0.6	0.3	2.8
10	Numidian of Cap Spartel	0.7	0.8	0.4	0.6	0.3	2.8
11	Achakarcalcarenites	0.7	0.8	0.4	0.6	0.3	2.8
12	Grotte Hercule	0.7	0.8	0.4	0.6	0.3	2.8
Weighted average		0.70	0.80	0.40	0.60	0.30	2.8
Weight		35%	20%	20%	15%	10%	100%

Note: *deterioration of geological elements(Dg), proximity to areas/activities with potential to cause degradation (PD), legal protection (LP), accessibility (Acc), density of population (DP), degradarion risk (DR).

Figure 15. Geosites of the Tangier Flysch Georoad on Google satellite image

Table 6. Technical characteristics of Tangier Flysh georoad

Longueur	75.01 Km
Difficulty	Low
Altitude min	-0 m
Altitude max	285 m
Start	Douare Dchicha
End	La grotte d'Hercule
Total time	8 h

Earth and help them better understand geological processes by illustrating theoretical knowledge with field observations. To build the foundations for the sustainable development of the Tangier and Fahs Anjra commune through geotourism, several lines of action have been drawn up:

a) Publish a geological guide with an inventory of the 12 geosites on the Flyshs georoad and continue to look for other geosites to highlight the municipality's diverse geological heritage.
b) Take actions to ensure sustainable development of the area, including geotourism projects, where the geosites mentioned above (and others not studied here) can be integrated not only as natural resources but also as natural heritage, offering local and foreign visitors the opportunity to get to know this exceptional geological heritage.
c) Signposting systems should be installed along the access roads to the commune and at the observation point of the geosite.
d) Creation of a TANGER natural history museum in the most visited area around Cape Spartel. The museum would serve geoeducation and geotourism, enabling visitors to learn about the rich natural heritage of the study area through guides and brochures containing information about geosites and the geodynamic history of the Rif.
e) Implementation of awareness plan for various stakeholders about the conservation of geological heritage, together with sustainable development strategies for the area;
f) Promote geotourism for the sustainable development of the commune of Tangier and Fahs Anjra by exploiting all the tools of technology, information and communication to enhance the best sites of geological interest in this commune.

CONCLUSIONS

Geosites in Tangier peninsula were identified and quantitatively assessed (12 geosites) to determine their scientific, educational, and touristic value, as well as their risk of degradation. The results allow for a case-by-case management strategy, enabling targeted conservation efforts for each geosite. While geosites have high scientific, educational and touristic value, their degradation risk is moderate. These findings strongly support the implementing geoconservation strategy, geoeducation, and geotourism. This leads to achieve the sustainable development and economic growth through job creation as well as the environment protection. However, a crucial element is raising awareness about geoheritage among all educational levels using tailored methodologies, recognizing the diverse needs and understanding of different audiences.

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