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METHODOLOGY FOR A MOROCCAN INVENTORY AND ASSESSMENT OF GEOLOGICAL SITES: A PROPOSAL TO BE APPLYED IN OTHER AFRICAN REGIONS

Metodología para un inventario y evaluación de sitios geológicos en Marruecos: propuesta para su aplicación a otras regiones africanas

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Abstract: *Officially, there is no exhaustive inventory of Sites of Geological Interest (SGI) in Morocco. Nonetheless, the Geological Service of Morocco started identification of these sites a few years ago, and published 9 volumes on the subject as geological and mining guides of Morocco. This was only limited to identification of SGI without their characterization and assessment, or identification of the threats that could affect them. In the last few years several PhD Thesis and research papers have dealed with this subject. Unfortunately, these initiatives are sporadic and far from establishing a global strategy for geoconservation and valorization of the Moroccan geological heritage. This paper proposes a global methodology for the inventory of geoheritage in Morocco by: i) providing a detailed synthesis of the research work on geoheritage in the world; ii) proposing the ways for assessing the Moroccan geoheritage at different scales (scientific education, geotourism, sustainable development, etc.); and iii) applying them to a wide variety of landscapes in Morocco. The obtained results and conclusions can be further extended to other African regions.*

Keywords: *Geological heritage, Sites of Geological Interest, inventory, assessment, Morocco*

Resumen: *No existe un inventario exhaustivo oficial de Sitios de Interés Geológico (SGI) en Marruecos. El Servicio Geológico de Marruecos ha promovido en los últimos unos años iniciativas para identificar estos sitios y las ha publicado, en 9 volúmenes, en forma de* *guías geológicas y mineras de Marruecos. Esta iniciativa sólo se limitaba a identificar los SGI sin caracterizarlos, evaluarlos o reconocer las amenazas que pudieran afectarles. En los últimos años varias tesis doctorales y trabajos de investigación han abordado esta cuestión. Desafortunadamente, han sido iniciativas esporádicas que no pueden cumplir el ambicioso reto de establecer una estrategia global de geoconservación y valorización del patrimonio geológico marroquí. En este trabajo se propone una metodología global para inventariar el geopatrimonio marroquí mediante: i) una síntesis detallada de trabajos de investigación llevados a cabo sobre geopatrimonio en el mundo; ii) la propuesta de criterios para evaluar estos resultados a diferentes escalas (educación científica, geoturismo, desarrollo sostenible, etc.); y iii) su aplicación a una gran variedad de paisajes de Marruecos. Los principales resultados y conclusiones obtenidos se pueden aplicar a otras regiones africanas.*

Palabras clave: *Patrimonio geológico, Lugares de Interés Geológico, inventario, evaluación, Marruecos*

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Introduction

Morocco, a country located at the north-western end of Africa in the connecting area with Western Europe, shows a geological history extending from 2700 Ma to the present (El Hassani *et al*., 2017) and an exceptional geological heritage. This richness is manifested by the appearance of a wide geodiversity, i.e., sedimentological, paleontological, petrographic, geomorphological, hydrological and structural resources, among others. Despite the high scientific value of this geoheritage in many moroccan regions, strategies for preserving it have not been undertaken systematically, and these resources have been largely and acritically threatened by touristic and other economic human activities that, in some cases, have consider it as an easy way for enrichment that, in any case, do not guarantee its use for sustainable development of indigenous people or its conservation. In this context, some initiatives are needed in order to establish its protection and preservation. Therefore, performing a strategy for inventory, characterization, assessment and protection of the geological heritage of Morocco becomes an imperative necessity and a national obligation. Identification of geological sites (according to Brilha, 2016) or, more widely, Sites of Geological Interest (SGIs) constitutes a primordial and first step for the inventory of this type of heritage, followed by the assessment and determination of their scientific value, potential of use, vulnerabilities and fragilities. The next steps lead to proposing measures for preservation and sustainable use.

Studies on the geological heritage of Morocco are not extremely abundant but it is possible to propose a good synthesis of works done until now on this subject. The first broad and remarkable work was initiated by the Ministry of Energy and Mines, and resulted in the publication of 9 volumes entitled "New geological and mining guides of Morocco" (Michard *et al.,* 2011), with the main goal of presentation of geological and mining sites in 17 geological itineraries (georoutes-like). Two other types of contributions were done by the Scientific Institute in the framework of its currently scientific research activities: (1) the lithotheque of Morocco (http://www.israbat.ac.ma/Lithotheque-du-Maroc/) that shows all the necessary information for the SGIs; and (2) the Atlas of geological collections of Morocco, developed under the aegis of Profesor Fidan (2017) that corresponds to a kind of computerized inventory of *ex-situ* objects of geological interest (1868 collected samples, coming from different regions of Morocco, which represent 15% of all geological collections).

Finally, several contributions have been performed as PhD Thesis and papers in the last two decades through personal initiatives (Malaki, 2006; El Wartiti *et al*., 2009, 2017; Tahiri *et al*., 2010; El Hadi *et al*., 2011, 2012, 2014, 2015; Nahraoui *et al*., 2011; Nahraoui, 2016; Enniouar *et al*., 2013, 2015; Errami *et al*., 2013, 2015a, 2015b; Fadli, 2014; Noubhani, 2015; Saddiqi *et al*., 2015; Bouzekraoui *et al*., 2017, 2018; M'Barki, 2017; Khoukhouchi *et al.* 2018; Arrad *et al*., 2018, 2020; El Hassani *et al*., 2017; Aoulad-Sidi-Mhend *et al*., 2019, 2020, 2022; Beraaouz *et al.*, 2019; Oukassou *et al*., 2019; Khourais *et al*., 2019; Berred *et al*., 2016, 2019a, 2019b, 2020; Berred 2020; Baadi *et al*., 2020; Mirari *et al*., 2020; Mehdioui *et al*., 2020; Lahmidi *et al*., 2020; Bouari *et al*., 2021; Berred *et al*., 2022).

This work faces the challenge to propose a standard methodology for the inventory of SGI in Morocco, as part of the national and international interest for conservation of the geological heritage. Moreover, the main results of this research can be applied to other African regions with similar characteristics as the case of the Maghreb countries.

Methodology

The Inventory of SGIs in Morocco follows a systematic approach, adapted to the Moroccan context, that insists on the good geological knowledge of this territory and that can also be applied to other Maghreb countries in Northern Africa. This method is subdivided into several steps (Fig. 1) that are decisive in any geoconservation strategy, and is based on (Brilha, 2005, Aoulad-Sidi-Mhend *et al.,* 2019, 2020, 2022): i) the identification, characterization and quantitative evaluation of the scientific value, the potential for use (educational and/or touristic), and the risk of degradation; and ii) the use of these results by decision-makers and actors of heritage protection for sustainable development (Aoulad-Sidi-Mhend *et al*., 2019). In parallel, this work could help to feed the database of geoheritage of Morocco, and to show and give publicity to the various components of the geology and the geodiversity of Morocco to specialists and amateurs.

In the last decades, many countries have developed national geoheritage inventories of SGIs, particularly in Europe, as the basis for their geoconservation policies (Wimbledon and Smith-Meyer, 2012). The inventory of geosites in the United Kingdom started in the 1950s and more than 3,000 sites are now protected as Sites of Special Scientific Interest (SSSI, Wimbledon *et al*., 1995). Spain also conducted a national inventory in the late 1970s, resulting in the selection of 144 geosites of national and international interest (Durán Valsero *et al*., 2005; Carcavilla *et al*., 2007, 2009). Switzerland inventoried its geoheritage in the 1990s and revised this inventory recently, recognizing 322 geosites of national importance (Reynard, 2012). In France the inventory, launched in 2007, documented 1131 geological sites in 2017. Similar situations can be found in Poland (Alexandrowicz and Kozlowski, 1999), Portugal (Brilha *et al*., 2005, 2010), and Russia (Lapo *et al*., 1993), Germany-Austria (Frey *et al*., 2021), Italy (Somma, 2022 and references therein), as well as in other countries in Africa: South Africa (Viljoen and Reimold, 1999), Kenya, Tanzania and Uganda (Schlüter *et al*., 2001), Ethiopia (Metaseria *et al*., 2004), and Namibia (Schlüter, 2008). The experience in these and other countries is used here to develop a standard inventory method for the geoheritage in two selected areas of Northern Morocco that can be adapted to other areas of the country, in particular, and the Maghreb, in general, and that develops along several phases.

Phase 1: Identification of SGIs

Identification and definition of SGIs must include a series of steps (Fig. 1): (1) *bibliographic and documentary compilation*, to analyzing different documents (geological studies, files and development projects) in order to infer the geological and topographical characteristics of the SGI; (2) *field data collection*, oriented to complete previous data and to ensure their accuracy (marked and approved trails and paved roads, network of associations and municipalities that carry out actions to open up the population and intervene to maintain some trails); and (3) look for finding and defining new SGIs.

Each SGI should be qualitatively evaluated by, preferently, multidisciplinary workteams and using the following international criteria: (1) *Representativity*, related to the relevance of the site to illustrate a geological process and contribute significantly to the understanding of the geological history of the region; (2) *Integrity*, related to the state of conservation of the site, considering both its fragility and vulnerability; and (3) *Rarity*, depending on the number of sites that have the same characteristic in a study area. The application of these criteria may involve deleting sites from the first established list because they do not reach the required standard, and adding other new sites.

In the areas to be inventoried, the actors of scientific knowledge, sensitization, and protection, whose activities are directly or indirectly related to the geological heritage, should be contacted (Aoulad-Sidi-Mhend, 2014), as they can be an important source of information to pre-establish a list of SGIs and of their situations. This will also allow focusing on sectors and routes to be priorized during the field inventory.

After discussion and validation, the working group can propose a list of potential SGIs that must be georeferenced and located on especific maps using Geografic Information System (GIS) tools.

Phase 2: Characterization and evaluation of SGIs

The characterization of SGIs (Fig. 1) requires the establi-

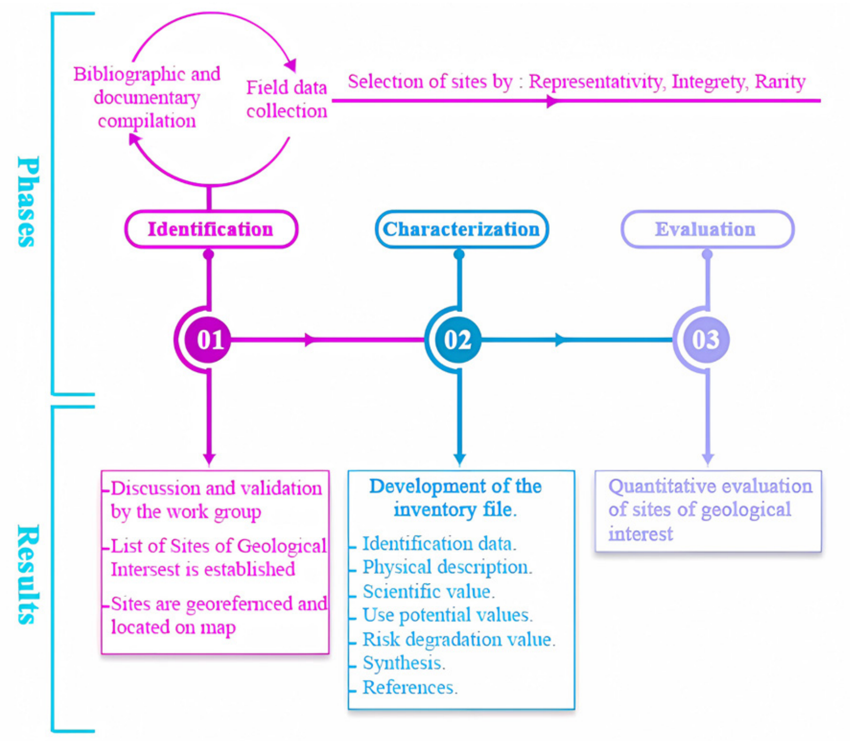

Fig. 1.- Methodology of the inventory of Sites of Geological Interest (SGIs).

shment of a scientific method to carefully identify and, if possible, to quantify, all the involved aspects needed for their correct definition. First, a review of the existing literature is needed to identify the procedures and techniques that must be used to characterize and evaluate each particular SGI. The authors of this method (Grandgirard, 1999; Reynard, 2012; Brilha, 2016) insist on the importance of clearly defining the objectives of the inventory for the proper selection of criteria and indicators. These criteria are mentioned in almost all literature concerning geoheritage (JNCC, 1977; Lapo *et al*., 1993; Wimbledon *et al*., 1995; Grandgirard, 1999; Alexandrowicz and Kozlowski, 1999; Parkes and Morris, 1999; Brilha, 2005; Pralong, 2006; Reynard *et al*., 2007; García-Cortés and Carcavilla, 2009; Fuertes-Gutiérrez and Fernández-Martínez, 2010; Díaz-Martínez and Díez-Herrero, 2011; Wimbledon, 2011; Gray, 2013; Reynard and Coratza, 2013; De Wever *et al*., 2014; Brilha, 2016; Reynard *et al*., 2016; Aoulad-Sidi-Mhend *et al*., 2019, 2020, 2022; Martín-Martín *et al*., 2021; Moliner-Aznar *et al*., 2021; Moliner-Aznar, 2022; Berred *et al*., 2022) and are hereafter presented in a new way that would be later used for definition and assessment of two case studies of SGIs in northern Morocco: the Talassemtane National Park and the Ghomara Coast.

Types of SGI	Brief description
Structural	Especially large geological sites such as folds (anticlines and synclines), thrusts, faults, etc.
Paleontological	Rocky outcrops containing fossils (bones, skeletons, leaves, lithified wood) in loose or consolidated soil, anaerobic environments (swamps) or ice (permafrost). They are of great importance for the reconstruction of the history of life.
Sedimentological	Sites in which the typical conditions of a sedimentation environment are visible (glacial, fluvial, lacustrine, eolian, etc.). Active SGI, which allow direct observation of sedimentary processes (*e.g.,* in alluvial fan), or recent archives of sedimentological features.
Petrographical, mineralogical and geochemical	Sites with singular mineral and/or ore deposits, type localities of peculiar rock lithotypes and/or showing rare geochemical features of particular interest (*e.g.*, subcontinental mantle rocks).
Stratigraphical	Outcrops presenting stratotypes for geological ages or formations, or typical profiles for one particular facies or paleoenvironmental transition (*e.g.* a glacial-interglacial transition) either in rocky outcrops or in unconsolidated Quaternary sediments.
Geomorphological	Both active erosion and sedimentation processes and landforms resulting from this activity (active alluvial zones, proglacial margins, debris flows, rock glaciers, lapies, scree cones), and Recent but now unactive surficial and loose formations (moraines, rock glaciers) and/or erosional landscape features (glacial potholes, lapiés of a superficial karst).
Hydrological and hydrogeological	Sites, where water is really the dominant element and that are special for particular, dynamics and/or physico-chemical characteristics of surface or underground water: thermal, mineral and karstic springs, losses, etc. This type of site is often confused with geomorphological or speleological sites such as waterfalls, gorges, meanders, karstic emergences, underground streams, etc.
Speleological	Cavities (caves and shelters, chasms and underground networks with a particular scientific (geological archaeological, anthopological, ecological or historical) value. By definition, many of thes sites overlap or are linked to other geomorphological or hydrogeological sites.
Geohistorical	Both key discovery sites in the history of the earth sciences and historic sites of geological resource exploitation.
Geocultural	Sites which, because of their natural characteristics, have played a particular role for mankind of in the course of its history. These sites do not necessarily have a strong intrinsic value for the earth sciences. It is their use by man that gives them value.
Geomaterial	This category includes the sites where there is an association of geological material (earth, water, area) with the know-how of Man through time, and using a technique. Examples of such sites are water and area mills, lime kilns, quarries and mines. These sites are of scientific, geotechnical, educational and tourist interest.

Table 1.- Typology of Sites of Geological Interest (SGIs) (Reynard et al., 2004a).

Phase 3: Proposal of the inventory-file of SGIs

Our working group has proposed a new *inventory-file* for SGIs (Fig. 1) that contains the following parts (Aoulad-Sidi-Mhend, 2019; Aoulad-Sidi-Mhend *et al*., 2019, 2020 and 2022): (1) identification data; (2) physical description; (3) scientific value; (4) potential use values (educational and/or touristic); (5) risk of degradation value; (6) synthesis; and (7) references. Each SGI must be characterized with the use of a file identifiying and revealing its typology (see below) or framework, its interest, its values, its impacts and how it can be valorized, in a way that allow these essential parametres to be quantified.

The identification data and the physical description of common typologies of SGIs are important parts of the *inventory-file*. Accordingly, the typology of the SGI must be stablished first and then, their features as sites of special geological interest (scientific and potential use values, risk of degradation, etc.) validated in some objective way and, if possible quantified. The typology varies according to the framework and interest of the geosite, which most common are: structural, paleontological, sedimentological, mineralogical, petrographical, stratigraphical, geomorphological, hydrological and hydrogeological, speleological, geohistorical, and geocultural types (Hinterman and Weber, 2001; Reynard *et al*., 2004; Table 1). This classification represents the geodiversity that exists in nature.

The scientific value of SGIs (Fig. 1) illustrate the importance of the geological processes responsible of their formation, allowing a better understanding of their geologic history (Brilha, 2016) and providing robust basis for protection proposals. Also, the scientific value enhances the scientific knowledge on which the SGI definition is based and its potential use as educational tool or touristic resource: as this knowledge must be transmitted and conserved for future generations (definition of heritage), SGI definition is best performed if it can offer educational tools (De Wever *et al*., 2006). Consequently, the assessment of SGIs is performed from quantification of the four main indexes mentioned above: scientific value (SV), potential educational use (PEU), potential touristic use (PTU) and degradational risk (DR). The purpose of this quantification is to reduce the subjectivity associated with any evaluation procedure. The results of this assessment are powerful tools for prioritizing enhancement and management. Sites with higher scientific value and increased risk of degradation should be given priority.

The synthesis part of the *inventory-file* aims to give a precise idea of quantitative and qualitative view on the essential properties of the studied SGI. The references of the *inventory-file* group together all the citations used during the description of the SGI. These are of primary importance because they allow us to indicate the authenticity of the information and give to the readers the possibility to access the sources of this information. This part also includes the names of the researchers of the working group that participated in the description and evaluation of the SGI.

Phase 4: Quantitative evaluation of SGIs

For determining the scientific value (SV) of SGIs, seven criteria that can be quantified are commonly used (Brilha, 2016; Aoulad-Sidi-Mhend *et al*., 2019, 2022; Martín-Martín *et al*., 2021; Somma, 2022): integrity (I), representativity (R), rarity (Rar), key locality (Kl), scientific knowledge (Sn), geological diversity (Gd), and use limitations (Ul). Quantification is based on the attribution of scores to the different criteria and indicators (Cendrero, 1996a, b; Coratza and Giusti, 2005; Pralong and Reynard, 2005; Pereira *et al*., 2007, 2010; Reynard *et al*., 2007; Bruschi and Cendrero, 2009; Reynard, 2009; Bruschi *et al*., 2011; Fassoulas *et al*., 2012; Pereira and Pereira, 2012; Bollati *et al*., 2013; Brilha, 2016; Aoulad-Sidi-Mhend *et al*., 2019; Mirari *et al*., 2020; Martín-Martín *et al*., 2021; Moliner-Aznar *et al*., 2021; Moliner-Aznar, 2022; Berred *et al*., 2022).

One particular SGI has elevate SV when it is one optimum representative case of a certain geological type or setting. The SV increases if the site is one international reference with publications of scientific relevance about it. Moreover, the SV increases if the SGI is well preserved and is easily available for future research (see Brilha, 2016; Aoulad-Sidi-Mhend *et al*., 2019, 2022, for details).

In contrast to the scientific value of a SGI, which is essential for determining its scientific importance and needs of conservation, the potential use values are reserved for determining the possibility of its use (Brilha, 2016; Aoulad-Sidi-Mhend *et al*., 2019, 2022; Mirari *et al*., 2020; Martín-Martín *et al*., 2021; Moliner-Aznar *et al*., 2021; Moliner-Aznar, 2022; Berred *et al*., 2022). These values are not related to the intrinsic characteristics of the SGI and are quantified by the PEU and PTU indexes (Brilha, 2016). For quantification of these values, the most commonly used criteria are: Vulnerability (V), Accessibility (A), Use limitations (Ul), Safety (S), Logistics (L), Density of population (Dp), Association with other values (Av), Scenery (Sc), Uniqueness (U), Observation conditions (Oc). In addition, other parametres such as Didactic potential (Dp) and Geological diversity (Gd) are added to evaluate the PEU, whereas the Interpretative potential (Ip), Economic level (El), and Proximity to recreational areas (Pr), are needed to evaluate the PTU. The evaluation of these elements should be a matter for specialists (see Brilha, 2016; Aoulad-Sidi-Mhend *et al*., 2019, for details). SGIs with high PEU values must be resistant to possible destruction (low vulnerability) and should be easily observed by students from secondary school to undergraduate university levels, accessible by all modes of transportation, and provide safety conditions to avoid reckless behaviors. Similarly, SGIs have a high PTU value when the geological features have remarkable aesthetic relevance, can be easily understood by visitors (tourists) without a geoscience background, and have low risk of environmental degradation by human activities (low vulnerability). Obviously, the existence of good equipment and visiting conditions are essential assets for the use of a geological site.

Quantification of the degradational risk (DR) complements the evaluation of the scientific value and potential use values of SGIs. It is a parameter of crucial importance for development and execution of assessment and management plans. The quantitative DR assessment proposed here considers recently published experiences and practices (Cendrero, 1996a, b; Brilha, 2005; Carcavilla *et al*., 2007; Reynard *et al*., 2007; García-Cortés and Carcavilla, 2009; De Lima *et al*., 2010; Pereira and Pereira, 2010; Fassoulas *et al*., 2012; Brilha, 2016; Aoulad-Sidi-Mhend *et al*., 2019, 2022; Mirari *et al.*, 2020; Martín-Martín *et al*., 2021; Moliner-Aznar *et al*., 2021; Moliner-Aznar, 2022; Berred *et al*., 2022). The DR quantification results from a combination of vulnerability and fragility, and is evaluated by using the following criteria: Deterioration of geological elements (Dg), Proximity to activities causing degradation (Pd), Legal protection (Lp), Accessibility (A) and Density of population (DP) (see Brilha, 2016; Aoulad-Sidi-Mhend *et al*., 2019, 2022, for details). SGIs have elevate DR when the main features of geological elements have a high probability of being damaged by natural factors, or by anthropogenic factors when the site is not under legal protection and/or it is located in areas with potentially dangerous human activities.

Results after the application of the methodology

To validate the above presented methodology, the Moroccan territory of the Talassemtane National Park and of the Ghomara Coast (TNP-GC) was used following previous inventory and assessment of its geological heritage by Aoulad-Sidi-Mhend *et al*. (2019, 2020 and 2022). This area (Fig. 2) makes part of the Mediterranean Intercontinental Biosphere Reserve and is included in the UNESCO tentative list of exceptional heritage of Morocco. This is located in the center of the Rif mountain range (NW Morocco), and covers an area of 100,000 ha. It has a high geological diversity with mountains that exceed 2000 m, karstic manifestations, structural formations, rivers and streams that wander through different types of rocks (sedimentary, metamorphic crustal rocks and sub-crustal ones, i.e., peridotite, etc.) before flowing into the Mediterranean Sea. In addition, it shows a rich biological diversity including endemic species of both plants (*Abies marocana*) and animals (such as the magot monkey: *Macaca sylvanus*), and a rich cultural heritage that testifies the passage of several civilizations that established there and left notable imprints at different scales.

Quantification

The TNP-GC area was subdivided into sectors (Fig. 2) where one hundred of SGIs were identified, although only the 42 more accessible sites were characterized and quantified for their inventory files with an assessment of the SV, PEU, PTU and DR indexes (Table 2). Scores between 1 and 4 were assigned to each criterion. The values of the inventoried SGIs were calculated by the sum of criteria weighted with the following formulas (for details see Brilha, 2016; Aoulad-Sidi-Mhend *et al.*, 2019, 2020, 2022; Martín-Martín *et al.*, 2021; Moliner-Aznar *et al.*, 2021; Moliner-Aznar, 2022):

(1) SV = 15%I + 30%R + 15%Rar + 20%Kl + 5%Kn + 5%Gd + 10%Ul

(1) PEU = 10%V + 10%A + 5%Ul + 10%S + 5%L + 5%Dpp + 5%Av + 5%Sc + 5%U + 10%Oc + 20%Dp + 10%Gd

(1) PTU = 10%V + 10%A + 5%Ul + 10%S + 5%L + 5%Dpp + 5%Av + 15%Sc + 10%U + 5%Oc + 10%Ip + 5%El + 5%Pr

(1) DR = 35%Dg + 20%Pa + 20%Lp + 15%Ac + 10%Dpp

The mean scientific value (SV) of SGI in the TNP-GC is high, on the order of 3.3 over 4 (Table 2) (see Aoulad-Si-di-Mhend *et al*., 2019, 2020, 2022). This value is supported by their good preservation status. There are better representative sites of certain geologic characteristics and types. However, there is some deficit of bibliographic references on their scientific content. Thus, 40% of the SGIs have very high scientific value, 40% have high value, and 20% have moderate value. The area contains 17 SGI with an SV of 3.6 and, therefore, can be considered as including SGIs of global geological interest, according to Brilha (2016).

The mean PEU value of SGIs in the TNP-GC is very high, 3.6 over 4 (Aoulad-Sidi-Mhend *et al.*, 2019, 2022). This value is supported by the resistance of SGIs to destruction due to anthropogenic action (low vulnerability), the existence of most SGI near paved roads and their accessibility by many types of transportation, the non-existence of use restrictions, and the association of all SGI with ecological and cultural values. Good observational conditions and readability of geological characteristics by students of all grade levels provide 76% of SGIs in the study area with very high PEU value, whereas 24% have the high PEU value.

The mean PTU value of SGIs in the TNP-GC area is of about 3.4 over 4 (Aoulad-Sidi-Mhend *et al.*, 2019, 2020), which is maintained by its remarkable landscape and aes-

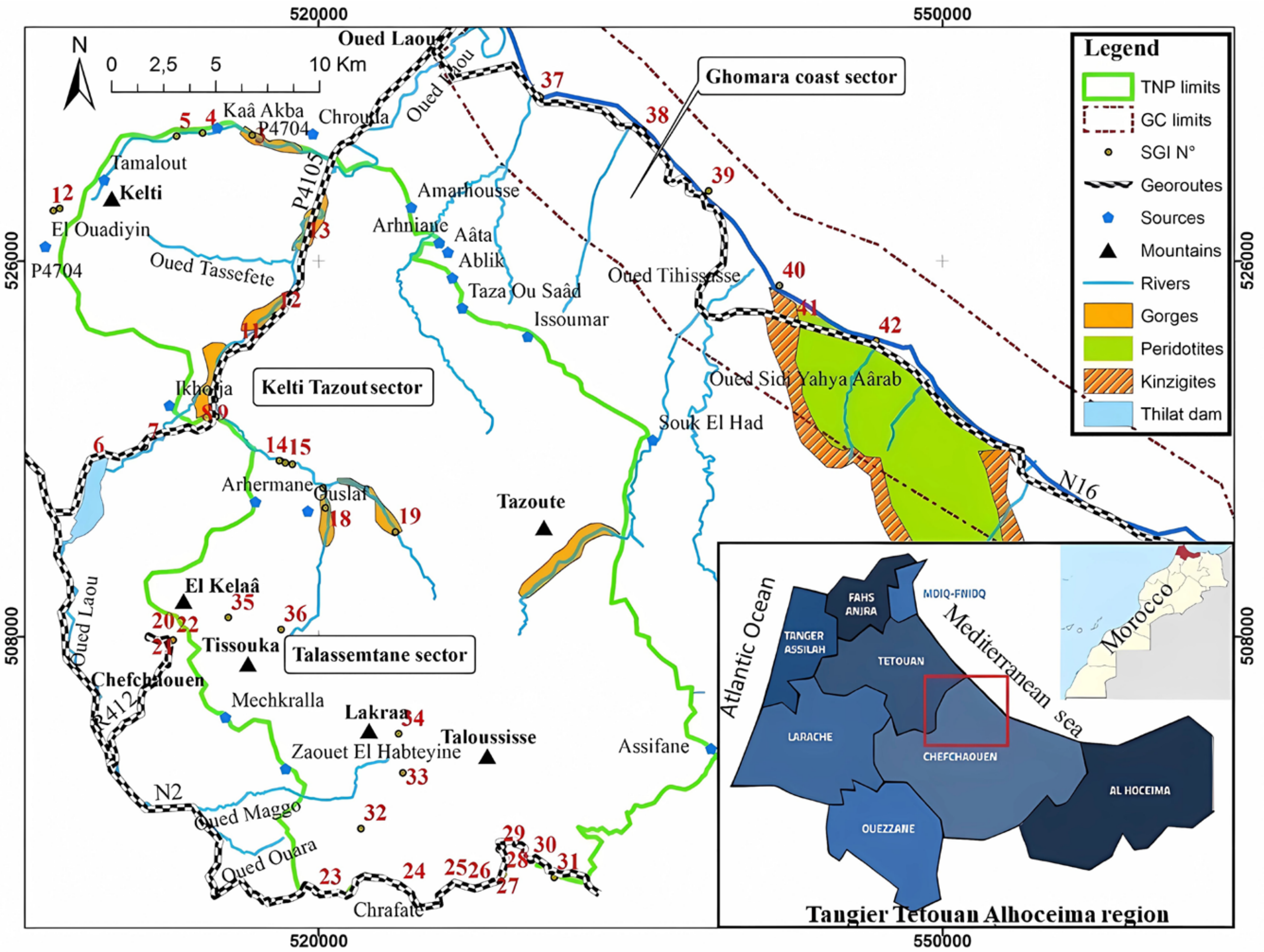

Fig. 2.- Sketch map of the study area, with the SGIs (red numbers) analyzed within the Talassemtane National Park and the Ghomara Coast (TNP-GC) area and its location in Northern Morocco (lower-right box).

N°	SGI Name	SV	PEU	PTU	DR
1	Lapiez of Jbel telloja	3.0	3.3	3.1	1.7
2	Raghdat Arimlal	3.3	3.3	3.2	2.1
3	Throat and river Tassikisste	3.6	3.7	3.5	2.1
4	Panorama Jbel Kelti	3.6	3.7	3.6	1.7
5	Khzanat Spring	3.3	3.5	3.1	2.3
6	Dam Ali Thilat	3.3	3.7	3.4	2.8
7	Granular quarry	2.1	3.6	3.2	3.0
8	Nummulitites limestone	3.6	3.6	3.3	2.8
9	Talâat Adrhosse	3.6	3.7	3.6	2.6
10	Oued Laou Throats	3.3	3.8	3.7	2.6
11	Folds of Ibouharen	3.3	3.7	3.6	2.8
12	Tirinesse Basin	3.6	3.8	3.4	1.9
13	Koudiat Achacha	3.6	3.7	3.4	1.9
14	Akchour Slide	3.0	3.6	3.4	2.8
15	Badlands of Talembote	3.1	3.6	3.4	2.2
16	Talembote Thrust	3.3	3.8	3.5	2.2
17	Dam Akchour	3.3	3.9	3.8	2.2
18	Throat and bridge of God of Oued Farda	3.3	3.3	3.2	1.8
19	Throat and Oued El Kelâa waterfall	3.3	3.2	3.1	2.2
20	Ecomuseum	3.1	4.0	3.9	2.0
21	Mirador of Sidi Abdelhamid	3.3	3.9	3.8	3.0
22	Ras Ma Spring	3.6	4.0	4.0	2.7
23	Phtanites of Bab Taza	3.2	3.6	3.3	2.8
24	Slide of Bouhala	3.0	3.7	3.4	2.2
25	Chrafate Spring	3.6	3.7	3.4	2.2
26	Chrafate breaches	3.6	3.8	3.5	2.5
27	Radiolarites of Beni Derkoul	3.2	3.6	3.3	2.5
28	Slide of Ametrasse	3.6	3.7	3.3	1.9
29	Panorama of Jbel Chrafate	3.6	3.6	3.2	2.3
30	Tertiary of Ametrasse	2.9	3.5	2.9	1.9
31	Kodiet Sbaâ Panorama	3.3	3.8	3.5	1.9
32	Raghdat S entrance of the TNP	2.4	3.6	3.4	1.9
33	Jbel Bou Sliman Panorama	3.3	3.5	3.1	1.6
34	Jbel Lakraa Panorama	3.6	3.5	3.4	1.6
35	Tissimlane flint limestone	3.0	3.5	3.1	2.0
36	Jbel Tissouka Panorama	2.7	3.5	3.2	1.6
37	Beach of Kaâ Asrasse	3.3	3.8	3.7	2.2
38	Micaschist of Targha	3.6	3.9	3.8	2.8
39	Gneiss of Stehat	3.6	3.8	3.7	2.6
40	Kinzigite of Beni Bouzra	3.6	3.8	3.8	1.9
41	Delta Tighissasse	3.6	3.9	3.7	2.8
42	Peridotite of Beni Bouzra	3.6	3.9	3.6	1.9
	Weighted average	**3.3**	**3.6**	**3.4**	**2.2**

Table 2.- Assessment of the SGI typologies inventoried in the Talassemtane National Park and the Ghomara Coast (TNP-GC).

thetic relevance, as well as the easy reading of geological elements by the general public. The low vulnerability of the environment to anthropogenic activity and the proximity of these SGIs to recreational areas enhance 33% of them to very high PTU values (Oued Laou Throats, Akchour dam, Ecomuseum, Mirador of Sidi Abdelhamid, Ras Ma spring, Kaâ Asrasse beach, Micaschiste of Targha, Stehat gneiss, Kinzigite of Beni Bouzra, Tihissasse delta, Peridotite of Beni Bouzra) and make them very interesting items for the development of geotourism.

The mean DR for SGIs identified in the TNP-GC is moderate, on the order of 2.2 over 4 (Aoulad-Sidi-Mhend *et al.*, 2019, 2020): 38% of the sites in the study area have a low DR but 62% of SGI have a moderate DR because their main geological characteristics have some probability of being damaged by anthropogenic activities or natural factors, and this is due to the deficit in people access control even though most SGIs have legal protection. This factor is affected by the proximity of the sites in the TNP-GC area to roads and to unexpected territorial developments.

Typology

The 42 SGIs quantified and studied in detail were grouped in the 7 types defined by Aoulad-Sidi-Mhend (2019) according to the types or processes of formation; their percentages are illustrated in the Figure 3. Their diversity differs from one sector to another: 6 types in the Kelti-Tazaout sector, 7 in Talassemtane and 3 in Ghomara Coast. Their dominance also varies in percentage, but the dominant typology is geomorphological (33%), followed by structural (21%), hydrological (12%), sedimentary (12%) and petrological (12%) types, with low percentage for paleontological and geomaterial types (5% each). Additionally, these types and processes can be grouped into 5 themes (Fig. 4) for the study area.

Georoutes

Aoulad-Sidi-Mhend *et al.* (2019, 2020) defined 4 georoutes by grouping most of the above-mentioned SGIs according to a number of constraints, especially related to accessibility, so that 30 SGIs were retained because of their accessibility values equal to 4 (located less than 10 m from a paved road with bus parking). Nonetheless, 12 SGIs from the total of 42 SGIs inventoried were not valorized as part

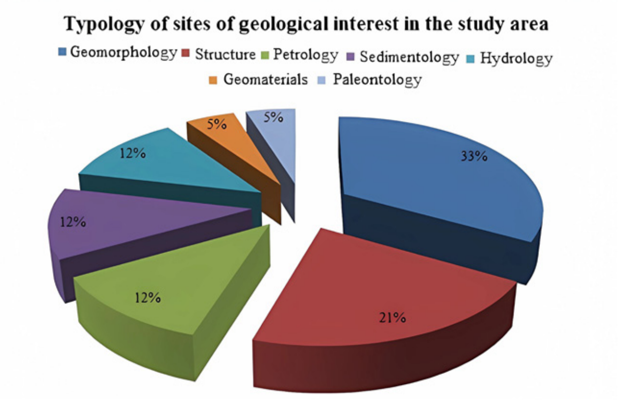

Fig. 3.- Average of the SGI typologies in the TNP-GC area.

Georoutes	Length	Route	SGI	Start	End	Themes
Oued Laou valley	26,5 km	P4105	8	Entered Dar Akobaa	North boundary TNP	Regional geology Water and Karst Exploitation of resources
Rueda Akchour	4,2 km	P4100	4	Entered Akchour	Akchour Dam	Regional geology Natural risk Exploitation of resources
Chaouen-Ametrasse	49,62 km	R412+N2	12	Ecomuseum sidi Abdel Hmid	Bouharchoun Coffee	Regional geology Natural risk Exploitation of resources Water and karst
Ghomara coast	38,25 km	N16	6	Kaâ Asrasse	Aaraben	Coastal dynamics Regional geology

Table 3.- Characteristics of the four proposed georoutes in the TNP-GC area.

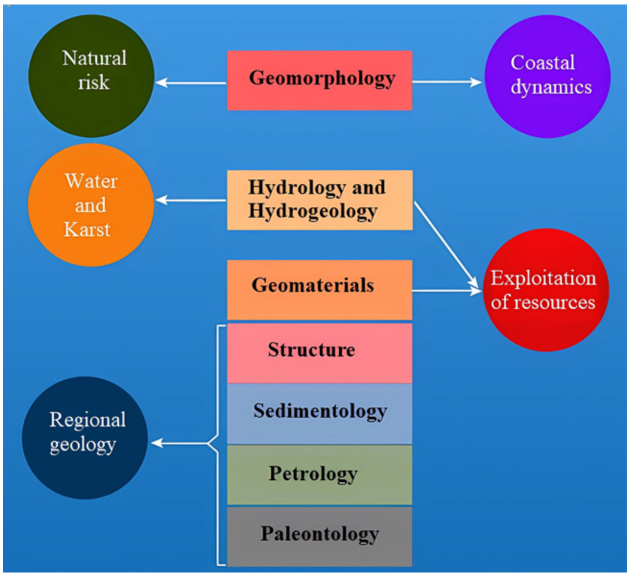

Fig. 4.- The five themes in the study area (Water and karst, Naturel risk, Coastal dynamics, Regional geology, Exploitation of resources) that group the 7 SGI typologies defined by Aoulad-Sidi-Mhend (2019).

of georoutes because of their low accessibility and weak touristic infrastructure. The adequate georoutes for a better development were found on two national roads (N2 and N16) and two provincial roads (P4105, P4100) in a territory endowed with touristic infrastructures of lodging and restoration. These routes are also served by frequent ways of transport and their level of safety is rather suitable. The four selected georoutes (Table 3) include outstanding SGIs with high SV, PEU and PTU scores that are characterized by thematic contents that meet pedagogical and didactic criteria very attractive for both specialized visitors and the general public.

Geological themes in the TNP-GC area

The SGIs defined by Aoulad-Sidi-Mhend *et al*. (2019, 2020, 2022) in the TNP-GC can be grouped in five main themes (Fig. 4) according to the dominant geological characteristics of the area: i) Water and karst (karst geomorphology and hydrology); ii) Natural risk (i.e., gravitational procceses and natural hazards); iii) Coastal dynamics; iv) Regional geology; and v) Exploitation of

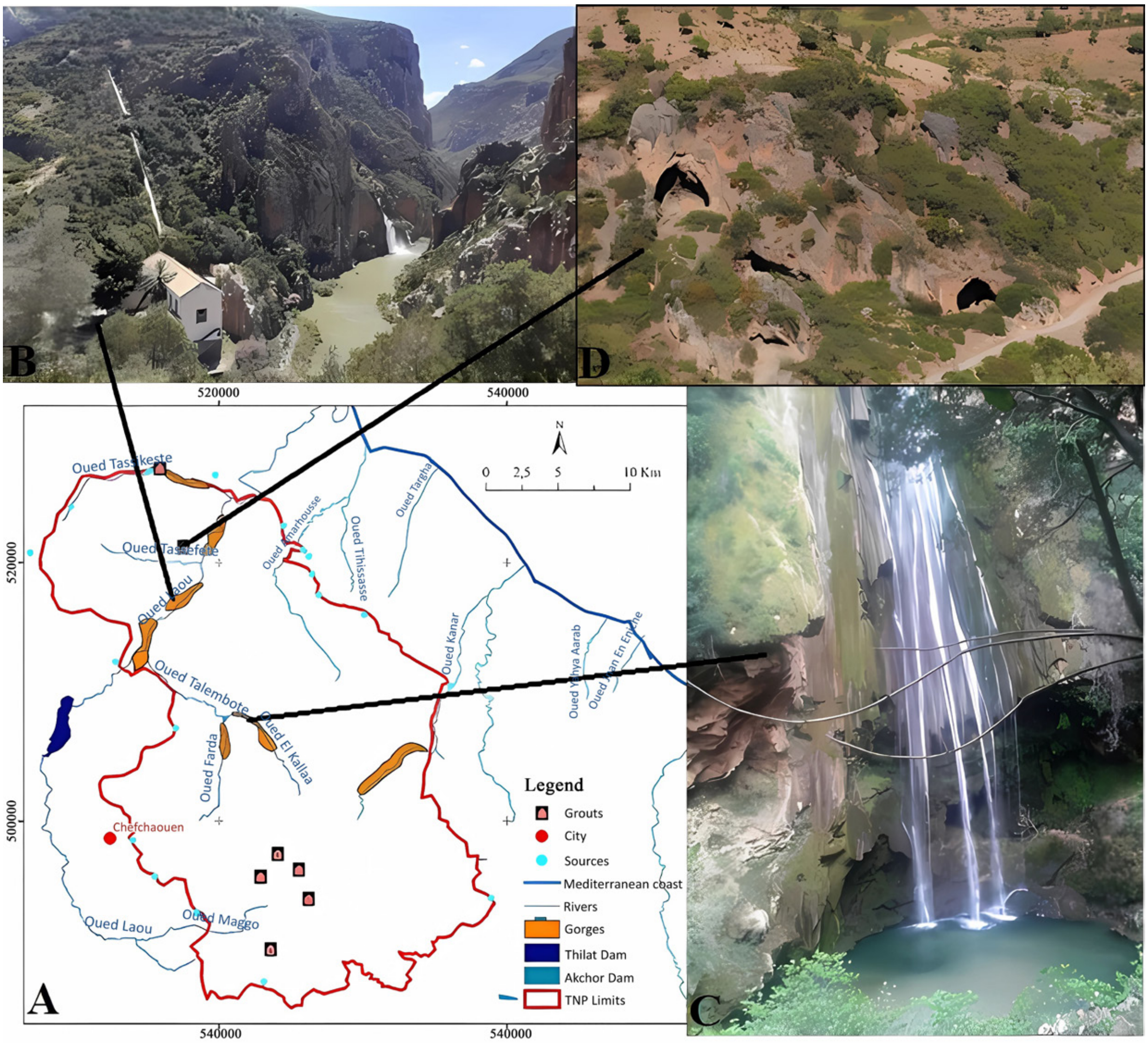

Fig. 5.- A) Map showing localization of structures and manifestations related to the water and karst theme in the area study; B) Throat and spring of Laou river; C) El Kalaa waterfall; D) Hattab cave.

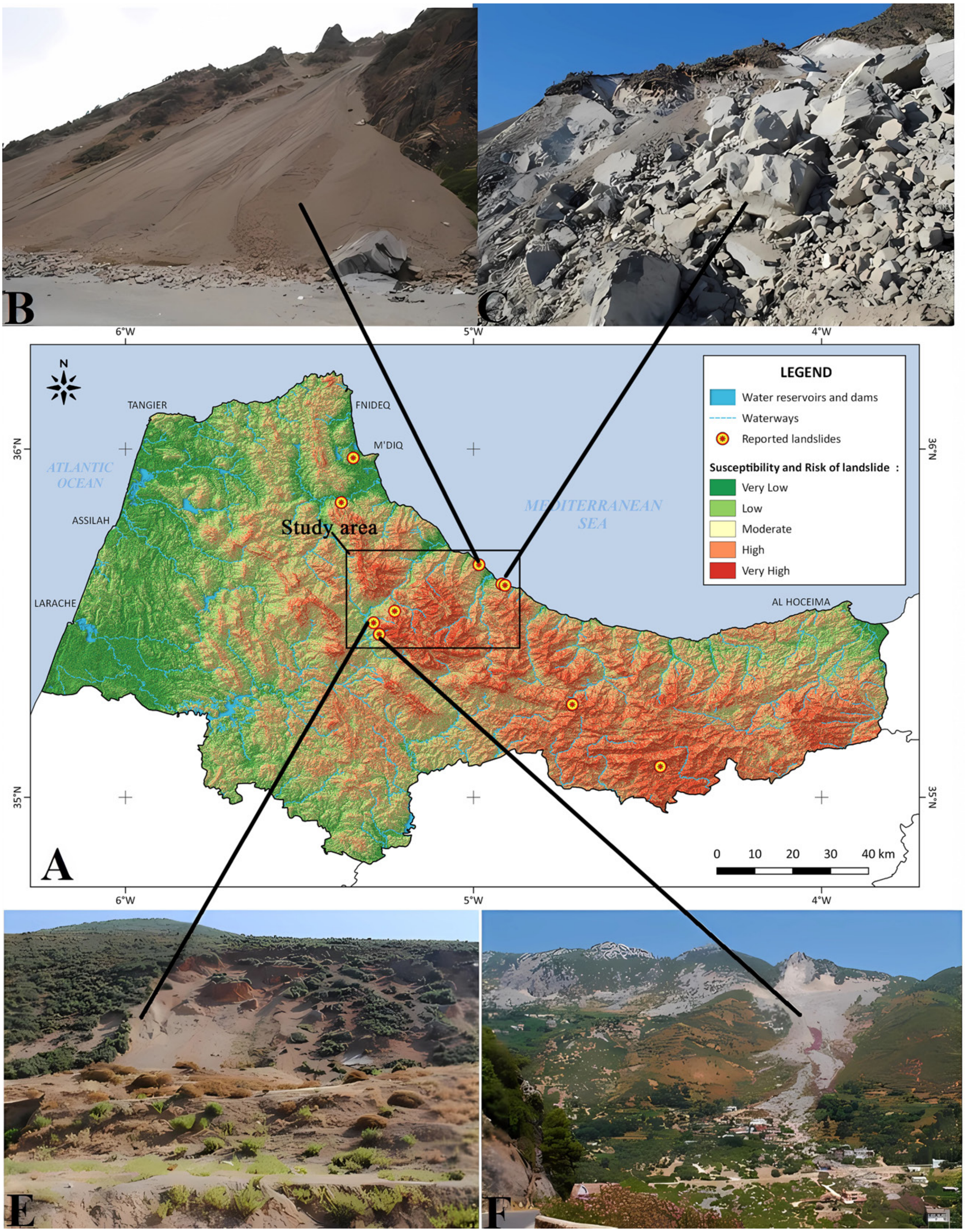

Fig. 6.- Gravitational instability theme in the study area. A) Landslide susceptibility map of the Tangier-Tetouan-Al Hoceima region (N Morocco); B) Azinti landslide; C) Beni Bousera landslide; D) Bouhala landslide; E) Ametrasse rockfall.

resources (i.e., geomaterials and the environment). The Talassemtane National Park receives significant amounts of precipitations and snowfall each year. This water is important for the physical environment, since it feeds the rivers of Laou (flow 2150 m^3/s), Tihissasse (Kanar and Bouhya), Ahrousse, Ihikkamane, Targha, Sidi Yahya Aârab and Amter (Fig. 5). In addition, water coming from calcareous reliefs (Dorsal) forms the power supply of the Thilat dam, the Akchour Lake, and dozens of springs (Ras El Ma, Maggou, Danou, Chrafate, Souyah, etc., see Fig.

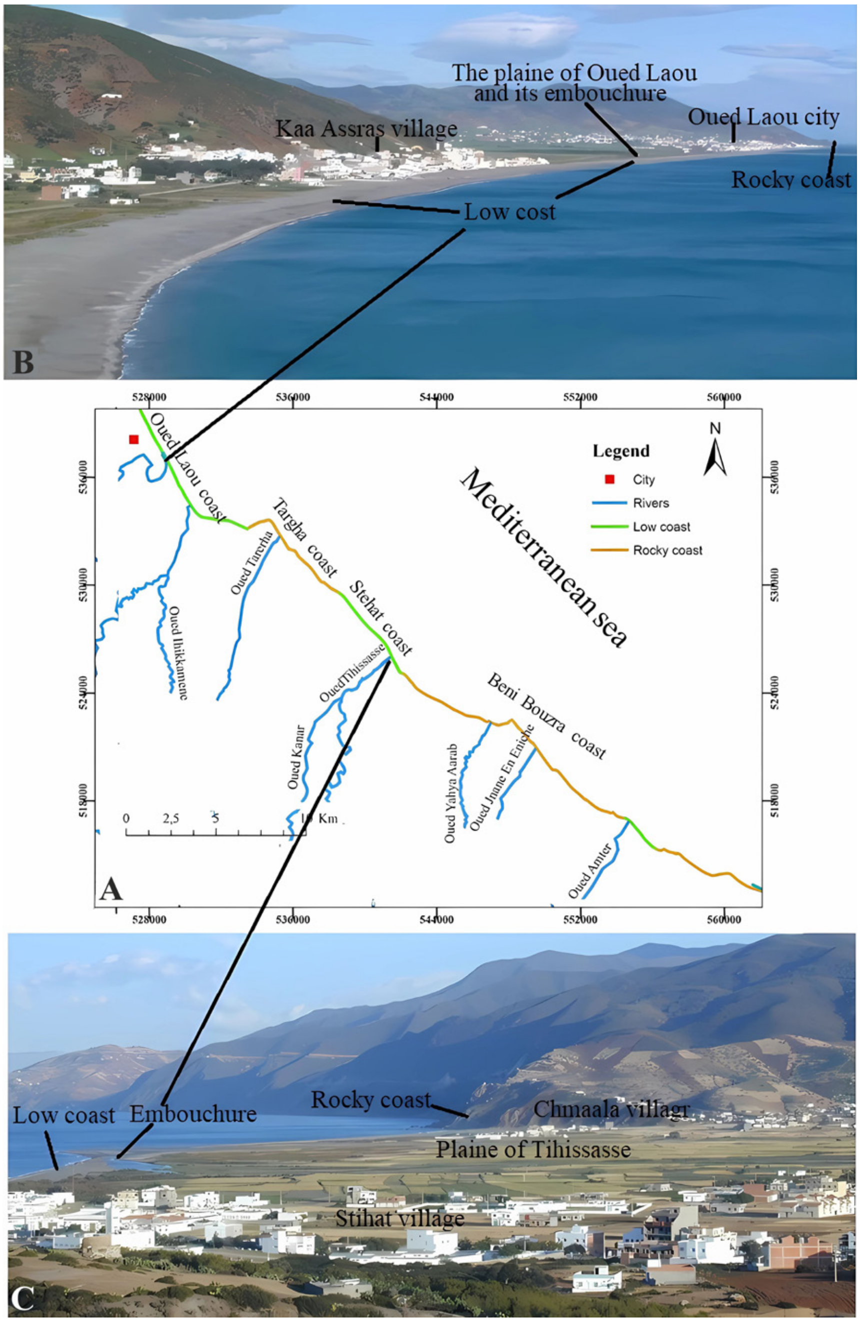

Fig. 7.- Coastal dynamics theme in the study area. A) Map representing the dynamics of the Ghomara coast; B) Panoramic view of the low coast in the Oued Laou area; C) Tighissasse River mouth delta in the low coast, with the rocky coast of Chmaala at the bottom.

2). Since the study area is largely constituted by calcareous-dolomitic rocks, both sectors of the TNP-GC show surface and underground karst networks with characteristics that make them unique in the region and even in the nation. Throats, caves, canyons, waterfalls and important springs (Fig. 5) are examples of karst manifestations that show high density, complexity and aesthetic values. As the karst network is created by the mechanical and/or chemical action of water on limestone, the water and the karst have been grouped in the same theme.

Considering the amount of elevate reliefs, the study area is characterized by numerous slope instability processes (Fig. 6). Gravitational dynamics activates land movements that are sometimes increased or triggered by processes related to diverse geological and environmental factors (seismics, lithology, structure, hydrology...). Instability is strongly favored by the lithology of the landscape, which is generally constituted by alternating more or less permeable rocks (marls, sandstones, and limestones) and impermeable layers with high clay content. Also, these landscapes and rock massifs are very fractured and affected by numerous faults and joints and receive a large amount of precipitation per year, which favours gravitational processes.

The Ghomara Coast (Fig. 7) has experienced coastal dynamics influenced by tides, waves and storms of the Mediterranean Sea, by the type of rocks of the coastline, and by the strength of the rivers and amount of alluvium that they supply. This dynamics results in a succession of low-relief coasts and cliffs, where both structural and lithological controls can be argued for the balance cliffs *vs* beaches.

The area has suffered both pre-Alpine and Alpine orogenies and, as a consequence, several geological structures appear, like thrusts, klippes, folds and faults, which are clearly visible at different scales in the area (Fig. 8). In relation to the Alpine Orogeny, the exhumation of the the second largest subcontinental mantle peridotitic massif in the World, the Beni Bouzra peridotite massif (equivalent to Ronda peridotites on the Betic side), evidences an important episode of the surrection of the internal part of the Rifian chain, with strong influence in its structural landscape. Other types of SGIs (sedimentological, paleontological and petrological, see Fig. 2) also allow understanding the regional geology, and the spatial-temporal (paleogeographical) evolution of the region and, because of that, have been classified within this category or theme.

Human development in the study area has been influenced by its relief. Actually, most of the sites surveyed also have some related historical, cultural or economic aspects (Fig. 9). Humans, through their history, have taken advantage of local geological characteristics as mines and quarries. For some sites, the relationship between humans and their physical environment is the most important aspect to highlight.

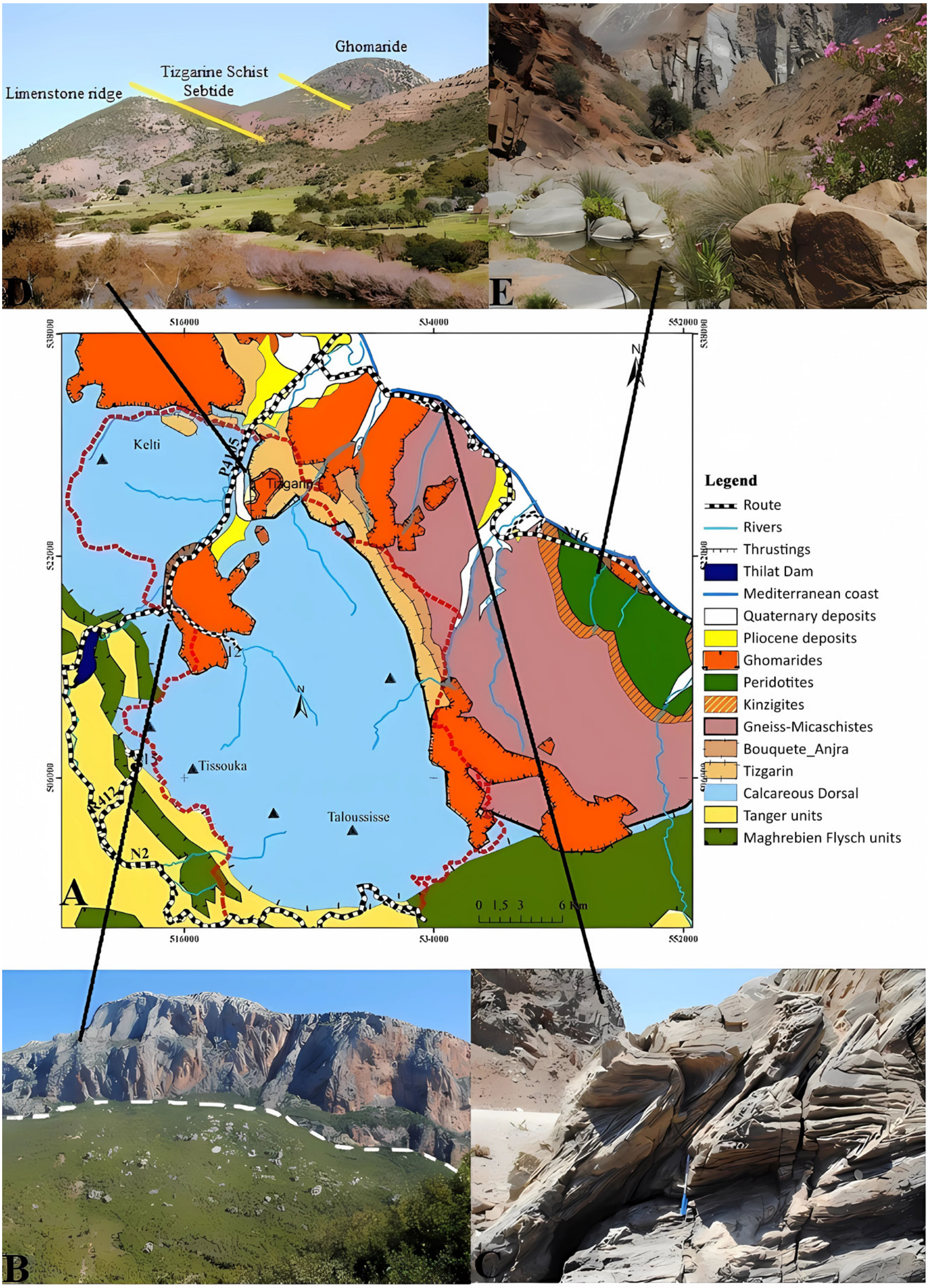

Fig. 8.- A) Regional geology theme in the study area; B) Talembote klippes; C) Micashist-type metamorphic rocks; D) Kodiat Achacha showing the structural relationship between the internal Rif units; E) Peridotites of the Aaraben Valley.

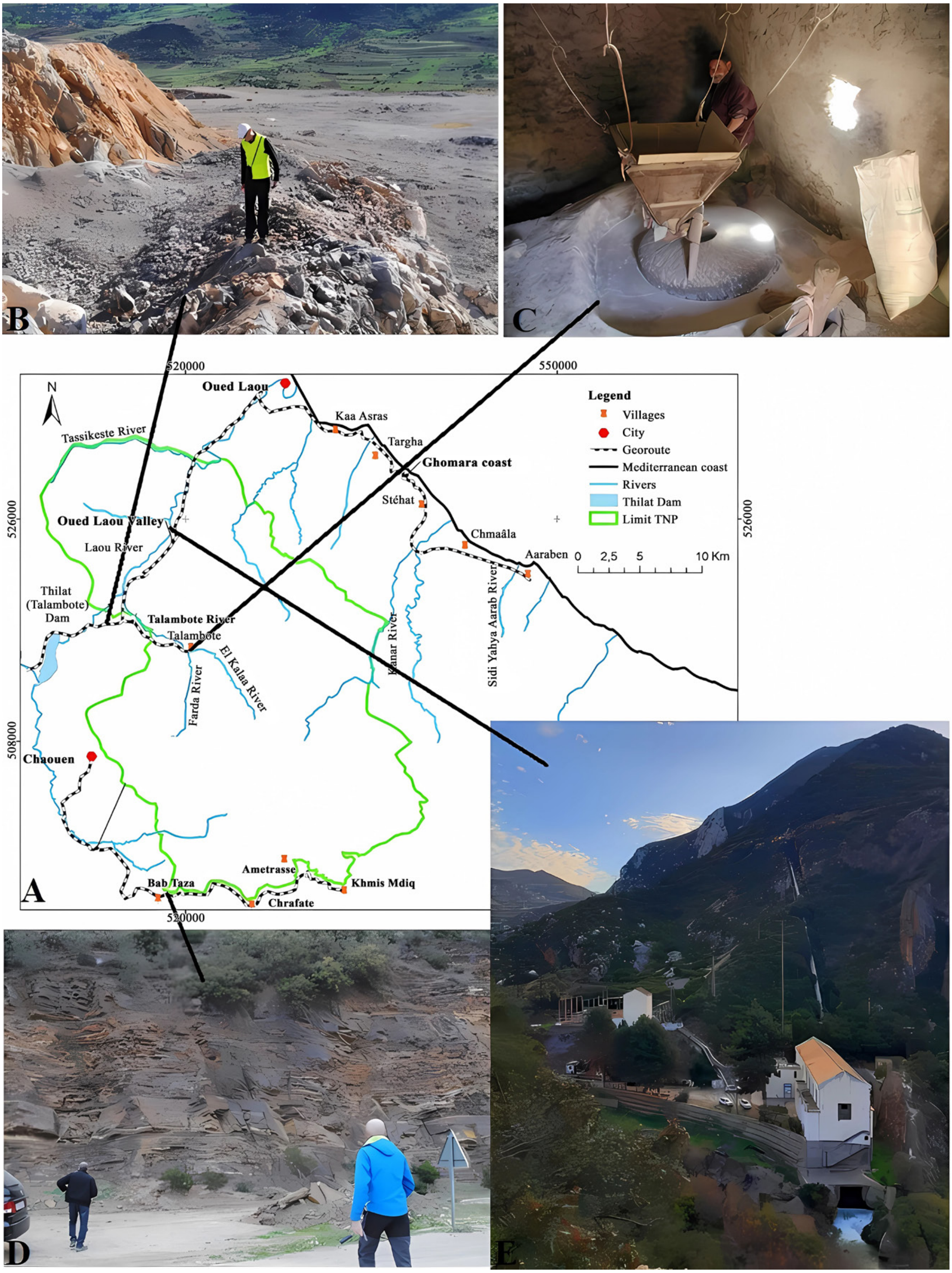

Fig. 9.- Geomaterials and energy theme in the study area. A) Map of study area showing Geomaterials and environment examples. B) Example of exploitation of natural resources in quarry for the extraction of granular material and blocks. C) Water mill of Akchour. D) Phtanites of Bab Taza, a geo-material exploited in the cement industry. E) Hydroelectric Power Station of Oued Laou.

Discussion

About the used methodology for assessment of SGIs in the TNP-GC area

The use of the methodology proposed by Brilha (2016) for the assessment of the 42 SGIs studied, confirmed the positive qualities that are attributed to the TNP-GC for the preservation of the geopatrimony and for sustainable human development in northern Morocco (Aoulad-Sidi-Mhend *et al*., 2019, 2020). In this evaluation, the attribution of scores to 37 criteria involved and divided into 4 parts (SV, PEU, PTU and DR) by our multidisciplinary work team has resulted in an objective ruling of the interest of each SGI in the TNP-GC area when compared to each other, and proves that the geodiversity of this area includes SGIs of not only local but also of international relevance with a solid and objective inventory.

The obtained assessment could contribute, in the near future, to the establishment of a geopark, in a perspective of preserving and integrating the resources of the study area as basic factors for the sustainable development (Eder and Patzak 2004; Zouros 2004; McKeever *et al*., 2010; Reynard *et al*., 2011; Aoulad-Sidi-Mhend *et al*., 2019, 2020). Geopark definition considers social, educational, economic and environmental as well as scientific aspects, and those have been valorized in the area. The first step in this procedure has already been undertaken through the award of a 2022 grant to accompany two UNESCO experts in order to prepare the Chefchaouen Geopark (TNP-GC) application file for the UNESCO Geopark label.

Posibility of exporting the methodology to other Moroccan and Nord African areas

The best way to ensure adequate protection for areas containing a large number of SGIs is to follow the integrated concepts of protection, education and sustainable development proposed by UNESCO in the Global Geoparks Netwok (GGN). This network promotes high quality standards in the services of natural areas, the dissemination of common strategies and best practices for conservation and the development of geotourism, as well as for exchange of knowledge and support for geological heritage areas worldwide (Eder and Patzak 2004; Zouros 2004; McKeever *et al*., 2010).

Morocco and other Maghrebian countries display a great diversity of landscapes and climates resulting in a high geodiversity, from the Mediterranean to the Sahara, and from the Atlantic to the Maghrebian Chains Highlands. These landscape areas contain, each, a large number of SGI memories of the history of the earth, and testify to their formation, including the first living (Precambrian) forms and paleoclimates, although they are exceptionally rare and are, unfortunately, in a process of destruction (Michard, 1976; Piqué, 1994; Piqué and Michard, 1989; Piqué *et al*., 2006). An essential first step in their protection and future sustainable use is the identification of the areas of geological interest that can be observed into five large landscape areas, from S to N (Fig. 10): i) Saharan and pre-Saharan

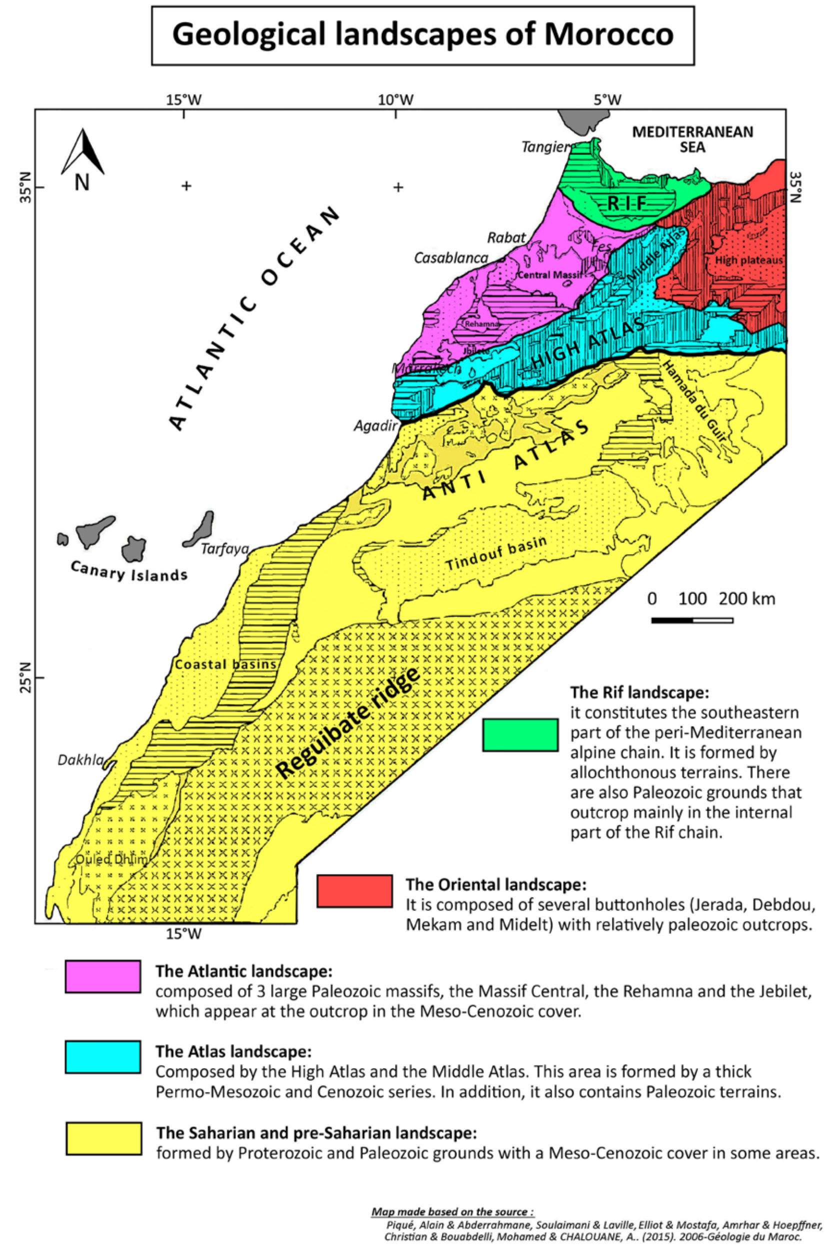

Fig. 10.- Map of landscapes and morphoregions of Morocco (modified from Piqué *et al.*, 1994).

regions; ii) Atlas Mountains; iii) Atlantic areas; iv) Eastern Morocco-Western Algeria; and v) Rif Chain.

The *Saharan and pre-Saharan* domain is spread over 5 regions of Morocco (more than 50% of the Moroccan territory) and also constitute a band to the south of the Atlas and Anti-Atlas Chains in N Africa (Fig. 10). Both areas are very rich in fossiliferous sites and Ag-Au-Ni-Co-Cu ore deposits. In the same way, the Man-Nature interaction has resulted in a large cultural heritage: archaeological remains, rock art, historical monuments, natural reserves. It is a very vast territory that is rarely little exploited rationally or frequented by tourists because of the absence of a proper infrastructure and of an inventory of sites that could highlight its natural and cultural potential. The Saharan part is located on crystalline Precambrian terrains testifying to the Eburnean orogeny (Fig. 11). It includes the structures that surround the Reguibate Ridge, which consist of cuestas constituted by Paleozoic sedimentary layers. The plateaus of the basin of Tindouf (or Draa: Morroco, Algeria, and Mauritania) consist mainly of limestone where Paleozoic terrains dominate and are crossed by a few rare wadis. In the pre-Saharan part, the Anti Atlas includes relief rising to altitudes of 2000 m in its western and central part (Jbels Bani and Ouarkziz) and consists of Precambrian terrains surrounded by sedimentary Paleozoic successions. To the east, beyond Zagora, the eastern Anti Atlas is less high and forms the Jbels Saghro and Ougnate. On its northern flank, the central Anti Atlas connects morphologically to the High Atlas by the advance of the Jbel Siroua. Apart from Siroua, the Anti Atlas and the High Atlas are separated by a set of depressions forming the South Atlasic Furrow, occupied by limestone and subhorizontal detrital series.

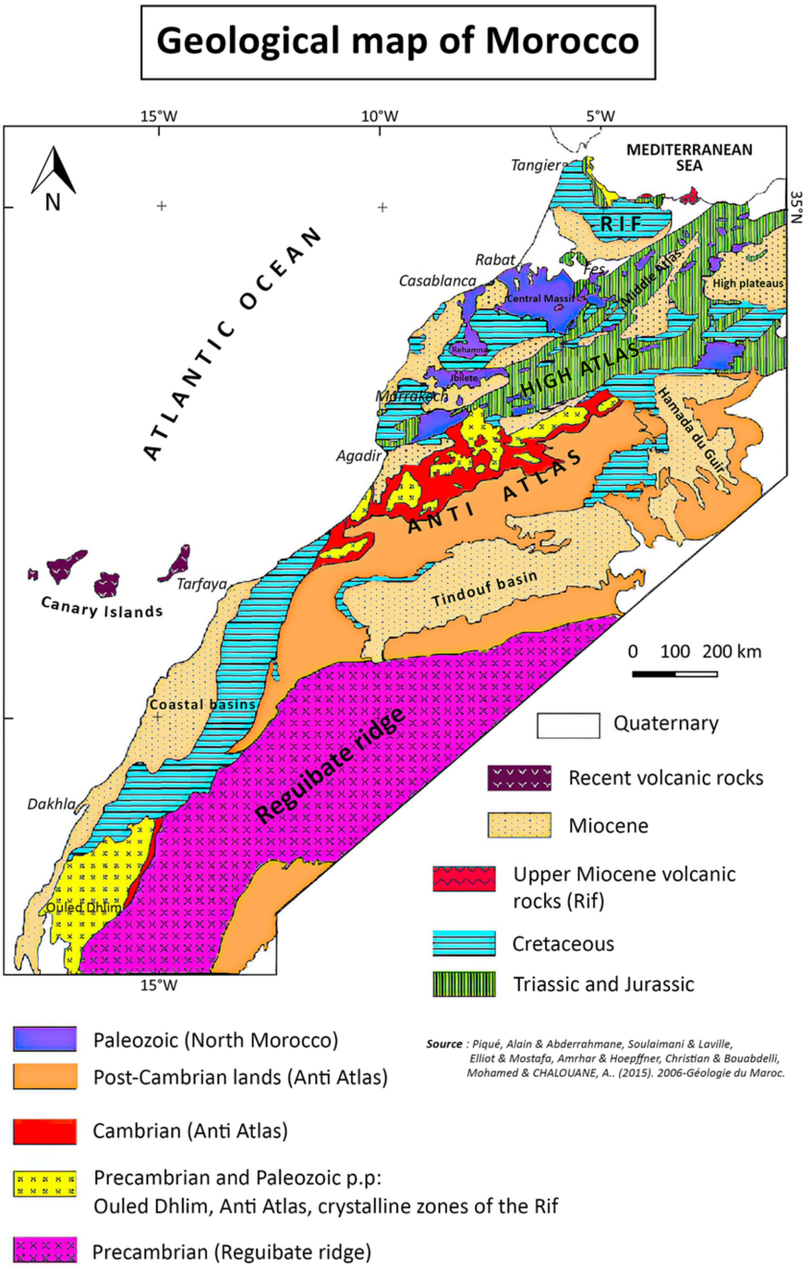

Fig. 11.- Simplified geological map of Morocco (modified from Piqué *et al.*, 1994).

The *Atlas Mountains* in Morocco consists of two mountain ranges (Fig. 10), the High Atlas and the Middle Atlas (Michard, 1976), that are relatively well watered where the great Atlantic wadis are born, including the Oum-er-Rbia and Moulouya wadies, which flow into the Atlantic Ocean and the Mediterranean Sea, respectively, as well as wadis that are lost in the Saharan endorheic basins, such as the Ziz Wadi. The Atlas Mountain extends eastwards through Algeria to Tunisia spanning over 2500 km and forming a barrier between the marine Atlantic and Mediterranean areas and the Sahara. The *High Atlas Range* (Fig. 10) is the most important morphological feature of Morocco, and separates the Atlantic plateaus and plains (to the north and west) from the Saharan domain (to the south and southeast). A very strong difference in precipitation, much more marked on the northern slope than in the south, is revealed by the presence of old and reforested forests contrast with the dryness of the southern slope of the chain, which is protected from the winds of Atlantic origin. The Western High Atlas culminates at the Jbel Toubkal at 4165 m in Morocco, while in Algeria it culminates at 2328 m in Jbel Chelia. The reliefs gradually lower towards the Tunisian Atlas, where the Jbel Chambi culminates at 1544 m. From the geological point of view, the highest part of the Western High Atlas is made up of crystalline

Precambrian and Paleozoic terrains (Fig. 11). Its folded Mesozoic cover appears in the west with the soft layers of the Argana corridor and the limestones of Ida-ou-Tanane. A folded cover is found at the northern limit of the Western High Atlas, from Imi n'Tanoute to Amizmiz and in the south, between the Tichka massif and the Souss plain. The Central High Atlas, from the Tizi n'Tichka to the valley of Oued Ziz, is occupied almost exclusively by folded Mesozoic series. Massifs of basic rocks outcrop in the region of Imilchil. The morphology of the Central High Atlas is dominated by tabular areas, at 2000 m altitude, such as the "Plateau des Lacs", separated by wrinkles where the Jbel Mgoun (4071 m) and the Jbel Azourki (3685 m) culminate. Beyond the valley of Wadi Ziz, the Eastern High Atlas raises its highest peaks at its northern edge, as the Jbel Ayachi (3760 m), which dominates the depression of Midelt. The chain is crossed by the road from Fez to Errachidia, which borrows the Tizi n'Talrhemt (2000 m) then the valley of Ziz. Beyond, the ancient lands reappear in the buttonholes of basins, as that of Tamlelt. The aridity increases towards the east and the landscape is, as in the Algerian Atlas, the esparto steppe. The *Middle Atlas Range* (Fig. 10) separates from the High Atlas in the region of Beni-Mellal and extends northeastward to Taza. The north-western edge is wooded with holm oaks and, above 1600 m, cedars, but in the south-eastern edge, which is much more arid, the holm oak gives way to esparto grass. The Middle Atlas includes two different structural entities: the "Tabular Middle Atlas", in the northwest (Ifrane area), and the "Folded Middle Atlas", in the southeast (Boulemane area). The Tabular Middle Atlas forms the limestone Causse, karstic plateaus at 1800-2000 m of altitude, dotted with volcanic cones and recent flows. In the Folded Middle Atlas synclinal basins are separated by ridge lines where the highest peaks stand out: Jbel Tichoukt (2796 m), Jbel Bou-Iblane (3190 m) and Jbel Bou-Naceur (3340 m). This area presents a natural and cultural diversity on a territory inhabited by vulnerable natives with deficit of necessary infrastructures. This territory hosts the only geopark in Morocco, the M'goun, named in 2014 by UNESCO thanks to the existence of complete dinosaurs skeletons and icnites, in addition to other natural, exceptional and rare cultural geosites. The ambitious plans for the sustainable development of the M'goun Geopark do not cover the entire area, and surely these richness can be an important item for sustainable development.

The *Atlantic area* spans between the Atlantic Ocean, the High Atlas, the Middle Atlas and the Rif (Fig. 10). This geographical area forms a quadrangle where three morphological and geological sets can be distinguished: Massifs and plains of Central Morocco, Coastal Plain, and Peripheral Depressions. The Central Massif is the major element of Central Morocco (Fig. 10) and is dissymmetrical, with average altitude rising towards the south-east towards the Middle Atlas, the highest point being the Jbel Mtourzguène with 1627 m. Rains are sufficiently abundant (500 mm per year) to maintain forests, often degraded, of holm oak. This massif is made up of folded, more or less metamorphosed sedimentary rocks and granitoids of Paleozoic age that make part of the Hercynian domain of Morocco. Further south, the Rehamna and Jbilete Paleozoic massifs are less elevated (700 m for the Rehamna, 1000 m for the Jbilete) but more arid, and emerge from plains with tabular and undeformed, Mesozoic and Cenozoic bedrock, like the Phosphate Plateau. The Coastal Plain (Fig. 10) extends from the Atlantic Ocean to the massifs and plains of central Morocco, with a flat relief except in the extreme south. In the north, the Chaouia shows mainly recent deposits with dark clay soils ("tirs"). The Paleozoic series only outcrop in the valleys of the coastal wadis and in that of the Oum-er Rbia, where they serve as anchors for several hydroelectric dams. The Doukkala extend the Chaouia to the south. The ancient bedrock does not outcrop except, very locally, in El Jadida. Mesozoic limestones are often covered by old consolidated dunes. In the Abda and, further south, the Chiadma, the coastal plain narrows and the Haha hills are, at 600-800 m altitude, the buttress of the High Atlas. To the north, the Tellian Atlas forms the Tell plains which, together with the adjacent valleys, contain the vast majority of the fertile land of Algeria and Tunisia. In Mauritania, the Atlantic Coastal Sedimentary Basin consists of sediments and sedimentary rocks from the Lower Cretaceous to the Quaternary. Finally, the Peripheral Depressions (Fig. 10) consist, in the north, of a depressed area which separates, over a width of a few tens of kilometers, from Rabat to Meknes, Fez and Taza, the Massif Central and the Rif. The marly and calcareous, marine and lacustrine deposits bear red soils ("hamri") that the annual volume of rainfall (500-600 mm) makes fertile without irrigation. The depressions of Haouz, between Jbilete and the High Atlas, and Bahira-Tadla, between Rehamna and the High Atlas, are filled with alluvial deposits eroded from the Atlas and are very arid, but irrigation can create very fertile areas. These are the most developed areas of Morocco with an important mass tourism infrastructure but are also far from conserving the natural and cultural heritage. Equivalent domains to the Peripheral Depressions are found in the Algerian Highlands (also known as High Plains or Algerian steppe) bordering the Tellian Atlas in the north and the Saharan Atlas in the south. They run to the east across Algeria from the Moroccan border to Tunisia at an average altitude of 1000 m.

The Eastern Morocco-Western Algeria area is limited to the north and west by the Rif and the Middle Atlas, to the south by the High Atlas, and it opens to the east to Algeria (Fig. 10). Rainfall from the Atlantic is blocked on the western slopes of the Middle Atlas, so this area is an arid region, with an annual rainfall of less than 300 mm. This plateau of one thousand meters of altitude extends the Algerian highlands. Its Mesozoic tabular cover is rugged with some low Paleozoic massifs of eastern Meseta (Debdou, Mekkam, Jerada, etc.) and a furrow where the valley of the Moulouya Wadi is lodged and constitutes a Cenozoic to Recent basin. This area shows an exceptional landscape thanks to its natural and karst potential and to the existence of traces of ancient civilizations, but it also suffers a deficit in touristic infrastructure and the misuse of these natural richness. Towards the east, the High Plateaux are located between the Tellian Atlas to the north and the Saharan Atlas to the south, and extend towards Tunisia with altitudes ranging from 900 to 1200 m, covering a total area exceeding 20 million hectares and widening to some hundred kilometers in the Algerian Constantinois. They consist of salt depressions, chotts or sebkhas, that constitute: i) the western steppes, to the south of Oran and south of Algeria, with altitudes decreasing from Djebel Mzi in the West to the Hodna salt depression in the Center; and ii) the eastern steppes east of Hodna, located to the south of Constantine.

The Rif Chain is a mountainous arc that constitutes the western end of the Maghrebian Alpine Chain that extends from Morocco through Algeria to Tunisia (Fig. 10). It is formed by Meso-Cenozoic allochthonous terrains overlapping the Meseta, with Paleozoic terrains also appearing in the inner part of the chain (Fig. 11). Towards the North this chain forms the southern branch of the Gibraltar Arc and connects with the Betic Cordillera in South Spain. The seismic activity in northern Morocco and Algeria is very important due to an intense Plio-Quaternary and recent tectonic activity generated by the NNW-SSE to N-S convergence between the African and Eurasian lithospheric plates at rates estimated to 0.5 cm/year in the Strait of Gibraltar. The chain is subdivided in Internal and Flysch plus External Zones. The Internal Rif makes the highest part of the range (Fig. 10), is located near the Mediterranean coast and consists of: (i) a fairly narrow inner strip of ancient (mostly Paleozoic) crystalline terrains that plunge under the sea along a rocky coastline; and (ii) an outer, Meso-Cenozoic carbonate belt (Dorsale) that also extends to the Bokkoya. The city of Tetouan occupies the cluse of the Martil River, which cuts at right angles to the ridge line. To the southeast of the ridge the Jbel Tidirrhine (2452 m) is the highest point of the Rif. On the whole, the high chain is well-watered, with rainfall in excess of 1000 mm per year, which allows for the establishment of oak and cedar forests. Towards the east, however, the altitude decreases and rainfall is less abundant, being the whole area drained by the Ouerrha Wadi and its tributaries. This domain can be followed into the Algerian Kabylia as well as the Flysch Zone and the External Rif (Fig. 10). The latter are mainly formed of Meso-Cenozoic shale, marl and sandstone, and constitute lower reliefs around the cities of Ketama, Ouezzane and west of Chefchaouene, with average altitude around 800-900 m and some higher massifs made of more resistant rocks that reach exceed 1600 m of altitude (Jbel Sougna, Rhesana, Outka). Like the Internal Rif, this region is well watered and drained by the Loukkos Wadi. Further south, soft reliefs of marl and clay surround the “Rides prérifaines”, where the Jbel Zerhoun, with its 960 m, dominates the plain of Meknes. Towards the east, the Flysch and External Zones follows in the largely allochthonous Algerian-Tunisian Flysches and Tellian domains, constituted by thin-skinned thrust nappes mainly made of Cretaceous to Neogene marls.

Problems when comparing at greater scale

Morocco is a natural space that presents a remarkable geodiversity, that is materialized by sites of high geological interest of different typologies, specific scientific interests (SV) and potential uses (PEU and PTU) but that, paradoxically, are vulnerable and characterized by risks of degradation (DR). The inventory made throughout the Moroccan territory to assess the value of each SGI reveals the state of infrastructure, with identification of trails, some easier and some others difficult to access. When an assessment and comparation at greater scale is intended (out of homogeneous areas like the PNT-GC), several criteria favor one site with respect to other according to its location in a protected natural area and/or a tourist area *vs* a non-touristic or simply a non-protected one. Therefore, the application of the above methodology at great scale require some modification of the proposed criteria and of their relative weights, depending if the area is protected or not and/or is a touristic or not. In that case, the affected criteria should be identified and removed by transferring their weight to other less weighted parameters (Tables 4 to 7).

The limitations of use (Ul, weighting 10% of the SV index and related to the existence of obstacles to visiting the site) is the only extrinsic criterion that disturb a proper comparison of the SV assessment among different GSIs (Brilha, 2016). Actually, it favors SGIs located in protected natural areas, especially if they are well accessible and without limitations (*e.g.*, in touristic areas). In the same way, the Key locality criterion (Kl weighting up to 20%) weakens SV in underdeveloped non-touristic areas, as it is commonly related to deficits in research budgets and, consequently, implies lower valuation of the existing scientific knowledge (Kn). Actually, natural areas normally have use limits and are negatively influenced by the latter two parameters. So, if the Ul parameter is eliminated and the Kl value reduced from 20% to 10%, the remaining 20% can be distributed to benefit other parameters that better valorize the SV and/or have lower weight in the SV assessment, such as the scientific knowledge (Kn) and the geologic diversity (Gd), which have 5% each. Then, for a better assessment comparation among the SV of different SGIs at greater scale we propose a re-evaluation of the parametres according to the values presented in Table 4.

Criteria to be evaluated	Criteria (Score 1 to 4)	Weighting (%)
Scientific Value (SV)	Integrity (I)	15
	Representativity (R)	30
	Rarity (Rar)	15
	Locality type (Kl)	10
	Scientific knowledge (Kn)	20
	Geological diversity (Gd)	10

Table 4.- SV Value and weighting proposal for comparing SGI typologies in other areas.

In the case of potential uses, “use limitations” related to the existence of obstacles to visit the site and “population density” related to the existence of a population near the SGI acting as potential visitors and with a weight of 5%, they are parameters with the highest influence in the PEU index when comparing SGIs located in different areas: the first (accessibility, with a weight of A=5%) negatively influences natural areas with limitations on use, whereas the second (population density with a weight of Pd=5%) will favor tourist areas that are more populated than natural areas or than other simply non-touristic areas. If both parametres are eliminated, the remaining weight of 10% can be added to the criterion “Association with other values” (Av), which remains less important for any assessment along the Moroccan territory than greater values of biodiversity and cultural diversity. With regards to the PEU, the didactic potential (weighting up to Dp=20%) is the most important parameter for assessment of a SGI in front of its geological diversity (weighting up to Gd=10%). Consequently, for assessment comparation of SGIs at greater scale in the educational field we proposed to eliminate from the PEU index the Gd parameter, and to add its weight to the Dp up to 30% (Table 5).

Criteria to be evaluated	Criteria (Score 1 to 4)	Weighting (%)
Potential Educational Use (PEU)	Vulnerability (V)	10
	Accessibility (A)	10
	Security (S)	10
	Logistics (L)	05
	Associations with other values (Av)	15
	Landscape (Sc)	05
	Uniqueness (U)	05
	Observation conditions (Oc)	10
	Didactic potential (Dp)	30

Table 5.- PEU Value and weighting proposal for comparing SGI typologies in other areas.

In the case of the PTU, the most influential criterion for SGI assessment and comparison at greater scales is the “Economic level” (weighting up to El=5%), as high income levels of people living near one SGI increase the probability of being this particular SGI more frequently visited. This criterion affects mostly different landscape areas of Morocco, where contrasted development between the north and south and the west and east are remarkable features. Actually, natural areas are mostly rural and with poor and vulnerable population due to the lack of sustainable development plans and problems related to climate change. If El is eliminated, this leaves a 5% weighting to be added to the “proximity to recreational areas” criterion, as proposed in Table 6.

Criteria to be evaluated	Criteria (Score 1 to 4)	Weighting (%)
Potential Touristic Use (PTU)	Vulnerability (V)	10
	Accessibility (A)	10
	Security (S)	10
	Logistics (L)	05
	Associations with other values (Av)	15
	Landscape (Sc)	15
	Uniqueness (U)	10
	Observation conditions (Oc)	05
	Interpretation Potential (Ip)	10
	Proximity to recreational areas (Pr)	10

Table 6.- PTU Value and weighting proposal for comparing SGI typologies in other areas.

In the case of DR the most reasonable option for greater scale comparison among SGIs is to maintain all the criteria, even if they can favor some areas over others, because to obtain the DR with all possible factors is the best way to avoid degradation and the best indicator of the protection that any SGI needs. As a general rule, SGIs with a degradation risk index greater than 301 (very high risk of degradation) should be subject to urgent protection measures, those with a DR of 201 to 300 (high risk) should be protected in the short term, and those with a DR of less than 200 (moderate risk of degradation) can be protected in the long term or left unprotected (Table 7).

Total scores %	Risk of degradation
< 200	Moderate
201- 300	High
301-400	very high

Table 7.- Ranges of the totals of the scores and classes of the categories of the risk of deterioration.

Concluding remarks

This research is focused on the assessment of the Moroccan geological heritage, in general, following a rationale gathering theoretical and practical aspects and aiming to propose modifications to make evaluation of SGIs at great scale as most objective as possible when applying the methodology to other areas. It is preceded by a case study performing an inventory-file of SGIs in the TNP-GC along phases of identification, characterization and evaluation. These results in identifying areas containing not only geological outcrops, but also amazing natural and cultural potential and favorable sites to any sustainable development action. Similarly, the contact with the population, the different actors and the analysis of the documentation collected on the area have allowed to distinguish a set of strengths and weaknesses for SGI definition in the TNP-GC that can help featuring SGIs in different landscape areas of Morocco objectively, and that can be applied to other African regions with similar characteristics, as in the case of other Maghreb countries.

The following main assets for SGIs definition in any Moroccan region are: (1) important and diversified natural resources (vegetation cover, biological, geological, and cultural diversity, etc.); (2) quality and diversity of local soil-related products (aromatic and medicinal plants, local products and original crafts like those associated with pottery). This has favored the development of entire villages that practice the pottery trade and sometimes linked to the woman, for example the village of Franali, in the North West of Morocco (Oued Laou); (3) diverse and spectacular landscapes; (4) well-preserved environment, especially on the high ridges of the Atlas Mountains and the Rif, the Sahara and pre-Sahara; (5) a local population able of adapting to environmental conditions through actions based on practices, traditional knowledge and a better understanding of the environment and its evolution; (6) existence of well-structured associations, mainly local and connected to academic institutions, with knowledge of the territory; and (7) structural development of the regions: airports, ports, railroads, TGV, highways, among others, and other infrastructures, which connect the different cities of Morocco and whose rational use can serve as an element of cohesion of the territory.

In front of these advantages, the main threats are: (1) degradation of natural ecosystems due to population growth; (2) risk of flooding at the edge of the rivers, desertification in the south, and erosion; (3) complicated administrative procedures; and (4) the distinct approaches of different actors on the territory, and their intervention without prior coordination sometimes leading to conflicts and differences in perception.

A solid strategy of sustainable development should be based on: (1) conservation and promotion of the geological heritage for creation of employement; (2) improvement of natural and cultural landscapes and quality of life in order to make more attractive territories for both natives and tourists; (3) integration of the geological heritage in the territory management and planning ; (4) communication and marketing through development of new information and communication technologies, and their use to valorize the heritage of Morocco; and (5) training in heritage professions and jobs. Consequently, the protection of the Moroccan geological heritage does not end in itself but pursues several objectives, the most important contribution deals with: (1) to establish solid bases for sustainable development through the geological and/or archaeological heritage, which will be achieved through activities supporting its natural and cultural values, ultimately benefitting the local populations from economic, cultural and social points of view; (2) to promote knowledge and spreading of earth sciences in territories hosting geological heritage, through education and dissemination; (3) to enhance and revitalize the geological heritage; (4) to promote natural and cultural tourism in a framework of sustainable development; (5) to revitalize economic activities in territories concerned by the geological heritage, in particular by supporting initiatives related to trade of local products; (6) to propose recommendations considering social, economic and environmental aspects, together with scientific aspects, to preserve the resources of the TNP-GC study area and to integrate them as fundamental factors of sustainable development; and finally (7) to promote establishing inventories of GSIs in each landscape area of Morocco and N Africa to deepen the scientific understanding of the geological diversity.

Most studies carried out so far on this subject are very descriptive and, in spite of their good scientific quality in general, they have focused on only a few aspects to serve as a basis for the establishment of real integrated and sustainable development project concerning the Moroccan geological heritage. In this sense, either in the area of Northern Morocco here studied and, in general in all the country as well as in other Maghrebian countries, and following the example of what has been done for cultural heritage, the following activities are needed: (1) developing of legislation by activating existing laws and authorities being demanding in their application to protect geological heritage; (2) increasing of sustainable development projects (considering the real needs of this population) able to integrate all resources, not just as resources but as heritage, offering the possibility to the local population to identify with them; (3) promoting these areas for sustainable geotourism using tools and means such as information and communication technologies, which allow illustrating the remarkable features of the natural heritage in the study area and in other areas; (4) setting up awareness campaigns for different actors on the preservation of natural heritage and the interest of establishing a strategy for its sustainable development.

Clearly, protection and assessment of heritage is not the business of a single actor. On the contrary, to achieve this goal several actors must work together and cooperate, each in the field of their specialty (Aoulad-Sidi-Mhend, 2014, 2019, 2020, Moliner-Aznar, 2022). Their backgrounds, concerns and interests differ, which makes difficult cooperation between them and coordination of their actions and, in some cases, impossible to achieve the goal fixed. However, handicaps bring also diversity of points of view, which can provide with strengths, making possible to group these actors in four categories according to their interventions: (1) the actors of the scientific knowledge (people who are in charge of studying and producing scientific knowledge on the geological heritage, mostly at universities and research centers); (2) the awareness-raising actors (people who are responsible for raising awareness among the public and decision-makers by orienting and disseminating knowledge for practical applications) including non-governmental organizations and associations, whether international, national or local, but also, certain ministries such as the Education Research and Innovation of African countries; (3) the actors of the protection (all the actors who have the responsibility to protect the geological heritage, by the force of the laws that allow them to fulfill their mission) are the different ministries and departments such as: Ministries of Sustainable Development, Culture and Tourism, Local Authorities, Agencies of Water and Forests and Land Management National Agencies of the different Maghrebian countries and regions in N Africa; and finally, (4) the economic actors (gathering all the companies and cooperatives working in the field of sustainable tourism and participating in the satisfaction of the needs of responsible tourists, such as accommodation, transport, guides, land products, crafts and commercial companies, extension and promotion, etc.) including the specialized tourist enterprises and their grouping, to better ensure their management and promotion.

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Author contributions

Manuscript preparation, AASM and MMM; methodology, AASM and MMM; figures, AASM; research/analysis, all authors; manuscript review, AASM, MMM and RH;

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