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MAPPING HYDROTHERMAL ALTERATIONS AND LINEAMENTS ASSOCIATED WITH EPITHERMAL AND MASSIVE SULPHIDES DEPOSITS OF TIFRAOUINE (NORTHWEST ALGERIAN COAST): USE OF LANDSAT 8 OLI DATA AND REMOTE SENSING

Cartografía de las alteraciones hidrotermales y de los lineamientos asociados a los depósitos de sulfuros epitermales y masivos de Tifraouine (costa noroeste de Argelia): Utilización de datos Landsat 8 OLI y teledetección

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Abstract: *Within the context of studying mineralizations related to the Miocene volcanic rocks from the northern part of Algeria, Landsat 8 OLI data and remote sensing techniques are carried out to characterize and map hydrothermal alteration outcrops in the Miocene volcanic rocks of Tifraouine on the northwestern Algerian coast, where several indications of mineralization are known. Short-wave infrared (SWIR) bands allowed for the identification of clay alterations, while the visible and near-infrared bands help in the detection of iron alterations. Red-green-blue color combination images of 6/7, 4/2 and 5/6 ratios were produced. Principal component analysis (PCA) was computed to characterise altered zones and extract lineaments. Matched filtering technique (MF) allows direct detection after applying minimum noise fraction (MNF) transformation and pixel purity index to the spectra in order to obtain a distribution map of the target mineral species in studied area. The remote sensing results combined with the structural geological data determine a relationship between mineralization and structural features and show that hydrothermal alterations are clearly controlled by tectonic. They are highly concentrated in the calderas zone and extend towards the Bouzedjar area which allowed checking the map performed according to the field studies. This will contribute to preliminary studies related to mineral exploration and enhance the mining potential of Tifraouine. The acquisition of supplementary data would allow us to extend this study in coming works.*

Keywords: *volcanism, alteration, Tifraouine, fractures, detection*

Resumen: *En el contexto del estudio de las mineralizaciones relacionadas con las rocas volcánicas del Mioceno de la parte norte de Argelia, los datos del Landsat 8 OLI y las técnicas de teledetección se han utilizado para caracterizar y cartografiar los afloramientos de alteración hidrotermal en las rocas volcánicas del Mioceno de Tifraouine, en la costa noroeste de Argelia, donde se conocen varios indicios de mineralización. Las bandas del infrarrojo de onda corta (SWIR) permitieron identificar las alteraciones de la* *arcilla, mientras que las bandas del visible e infrarrojo cercano ayudaron a detectar las alteraciones del hierro. Se obtuvieron imágenes de combinación de colores rojo-verde-azul de proporciones 6/7, 4/2 y 5/6. Se realizó un análisis de componentes principales (PCA) para caracterizar las zonas alteradas y extraer los lineamientos. La técnica de filtrado emparejado (MF) permite la detección directa después de aplicar la transformación de fracción de ruido mínima (MNF) y el índice de pureza de píxeles a los espectros, para obtener un mapa de distribución de las especies minerales objetivo en el área estudiada. Los resultados obtenidos por teledetección muestran que las alteraciones hidrotermales están claramente controladas por rasgos tectónicos. Están muy concentradas en la zona de las calderas y se extienden hacia la zona de Bouzedjar, lo que permitió comprobar el mapa realizado según los estudios de campo. Esto contribuirá a los estudios preliminares relacionados con la exploración minera y mejorará el potencial minero de Tifraouine. La adquisición de datos complementarios permitirá ampliar este estudio en los próximos trabajos.*

Palabras clave: *vulcanismo, alteración, Tifraouine, fracturas, detección*

Labdaoui, B., Benali, H., Boughacha, A., Moussaoui, K., 2023. Mapping hydrothermal alterations and lineaments associated with epithermal and massive sulphides deposits of Tifraouine (northwest Algerian coast): Use of Landsat 8 OLI data and remote sensing. *Revista de la Sociedad Geológica de España*, 36 (1): 3-15.

Introduction

Information about the Earth's surface can be collected by satellite remote sensing, without any direct physical contact. This process consists in collecting emitted electromagnetic energy, which is then analysed and interpreted. Worldwide, several studies have been conducted in the identification of minerals forming zones using remote sensing (Ninomiya, 2003; Azizi *et al.*, 2007; Mia and Fujimitsu, 2012; Rockwell, 2013; Abdelnasser *et al.*, 2018; Cardoso-Fernandes, 2019; Adiria *et al.*, 2020; Peleli *et al.*, 2021; Yousefi, 2021). The supergene phase and iron oxides occurred on the surface are indicators of mineralization (Torres-Vera and Prol-Ledesma, 2003; Eisele *et al.*, 2012; Pour *et al.*, 2013) therefore, remote sensing technologies are suitable tools for identifying hydrothermal alterations, especially in the early stages of investigation, in the analysis of the relationship between mineralizations and structural elements as demonstrated in Sar cheshmeh copper mining district in Iran (Pour and Hashim, 2015), in Tirka Area, Toroud, NE Iran (Mina *et al.*, 2019) and in the Guelma basin (Northeastern Algeria) (Nait Amara *et al.*, 2019). The Landsat 8 satellite was launched on February 11, 2013. It was developed by NASA in collaboration with the USGS (United States Geological Survey). The thermal instrument (TIRS) carries two additional thermal infrared bands, band 10 and band 11. The Operational Land Imager of Landsat 8 data (OLI) is able to identify hydrothermal alterations due to their absorption and reflectance features that occur in this range (Ali and Pour, 2014; Amin Beiranvandet *et al.*, 2014; Mwaniki *et al.*, 2015; Wang *et al.*, 2017). In northwest Algeria, more particularly in Tifraouine, mineralizations related to hydrothermal alteration are hosted in Miocene volcanic rocks. The volcanic massif of Tifaraouine belongs to the volcanic group of the Sahel of Oran. The region has been the subject of geological and geophysical studies revealing the existence of several mineralization indexes. The region's mining potential started in colonial times (Glaçon, 1967). Several small deposits have been discovered during prospecting campaigns, the most important is the Oued Chadia magnetite deposit, discovered and prospected in 1856 until 1859.

The purpose of this article is to present a distribution map of altered rocks by the use of satellite remote sensed data and to compare it with that obtained by field studies. In this study, different approaches of detection methods were used with various image processing and enhancement techniques applied to Landsat 8 data (OLI). These data have been chosen in this study due to its availability and resolution. More than that, The OLI and TIRS sensors of Landsat 8 data improve the radiometric performance of the signal-to-noise ratio and allow data quantification with better land coverage (Pour and Hashim, 2015). Indeed, several studies around the world in geosciences proved that remotely sensed multispectral data is a powerful tool for mineral exploration, identification of hydrothermal alteration zones and determination of structural features allowing the acquisition of valid results (Ducart *et al.*, 2016; Hu *et al.*, 2018; Ibrahima *et al.*, 2018; Nait Amara *et al.*, 2019; Adiria *et al.*, 2020; Peleli *et al.*, 2021). Thus, the main objectives of this work are to map hydrothermal alterations in the Miocene volcanic rocks of Tifraouine and extracting lineaments to solve the following problems: how does hydrothermal alterations occur in Tifraouine? What is the relationship between structural elements and hydrothermal alterations? Are there similarities between the results of field studies and those of remote sensing?

Geology of Tifraouine

The Miocene volcanic rocks of Tifraouine are located on the northwest Algerian coast, forty kilometers southwest of

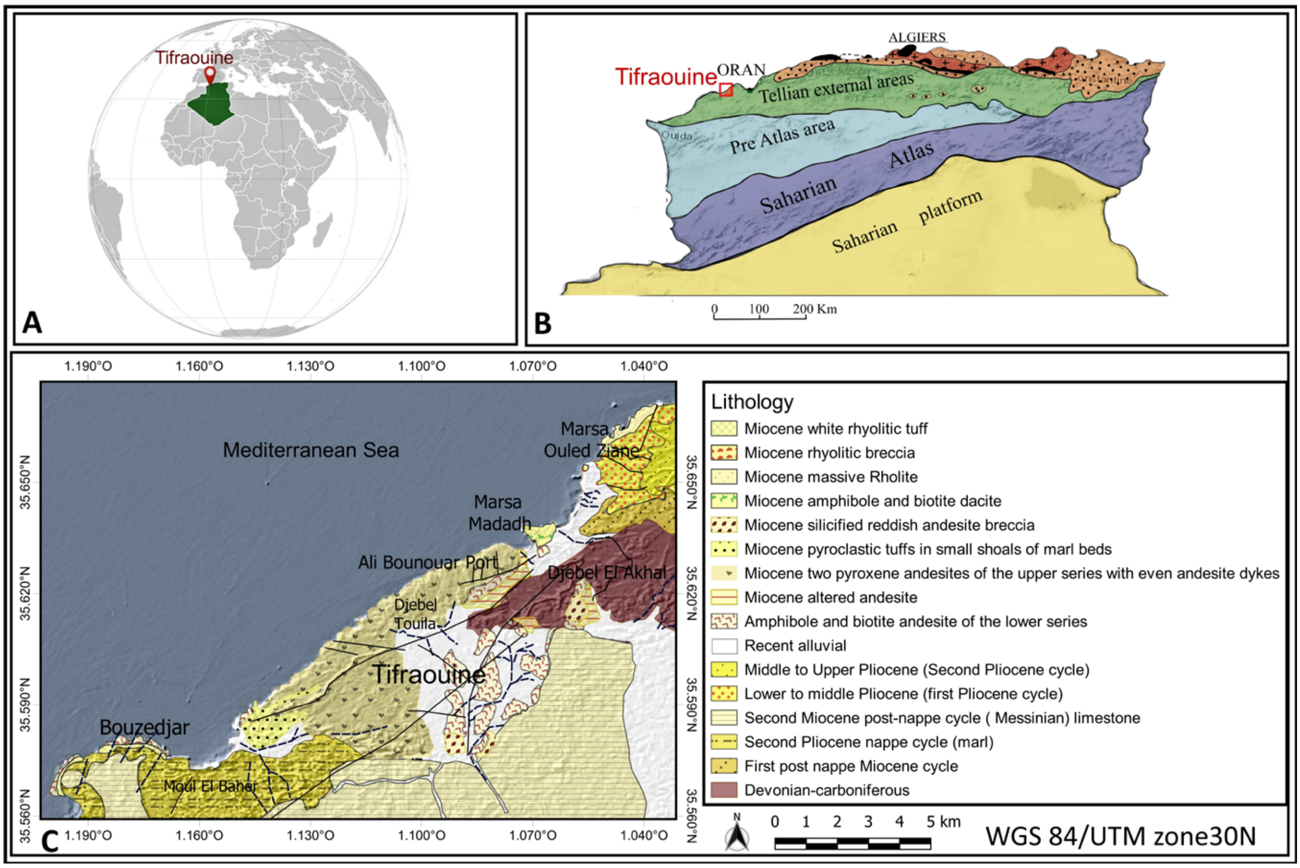

Fig. 1.- A) Location of the study area. B) Situation of Tifraouine in relation to the major morphological complexes of northern Algeria (Himri, 2008).C) simplified geological map of Tifraouine (Megartsi, 1985).

Oran, thirty kilometers north of EL Amria city (Ain Temouchent) and ten kilometers northwest of the Sebkha of Oran, between Bouzedjar Port to the southwest and the Ali Bounouar Port to the northeast (Fig. 1). This region is characterized by a warm temperate climate with an annual rainfall of about 378 mm and sparse Mediterranean vegetation. It is marked by moderate land elevations, with altitudes of no more than 300 metres (Belmouhoub, 1995; Benali, 2007). Thanks to geological studies, several gold and copper targets have been detected in Tifraouine with concentrations of elements such as copper, gold, nickel, vanadium, lead and zinc (Mouffok, 1999; Souahlia, 2001; Belmouhoub, 2004). In the context of the polymetallic mineral research related to volcanic and volcanosedimentary rock of northwestern Algeria, geologists of the Algerian National Office for Geological and Mining Research (ORGM) suggest the existence of a Kuroko-type deposit in Tifraouine (Belmouhoub, 2004). To better characterize mineralization and hydrothermal alterations, three boreholes performed by the ORGM were studied by Belmouhoub (2004) and Benali (2007). In 1996, mapping the distribution of hydrothermal alterations in Tifraouine was realized by the ORGM through field studies, that shows the degree of hydrothermal alteration in the caldera of Tifraouine (Fig. 2).

The Miocene volcanic rocks of Tifraouine belong to the volcanic complex along the coast of Oran in western Algeria, situated in the western sector of the Tellian external area that forms the southern segment of the alpine chain

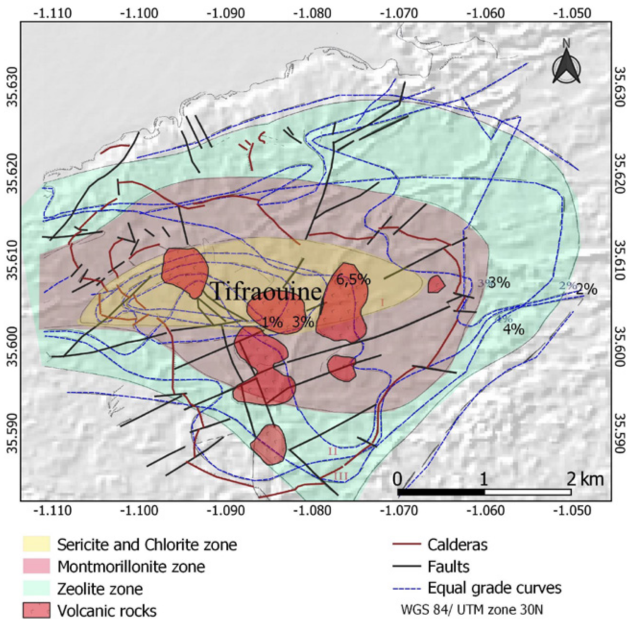

Fig. 2.- Hydrothermal alteration map of Tifraouine developed according to field studies performed by Belmouhoub (2004).

(Fenet, 1975; Guardia, 1975; Megartsi, 1985; Ciszak, 1993; Pique *et al*., 1998) (Fig. 1). It consists of folded Mesozoic formations below Cenozoic rocks and intense Miocene volcanic activity that began approximately 9.7 million years ago (lower Tortonian) and ended 7.9 million years ago (late Tortonian) (Megartsi, 1985; Benali, 2007).

The common rocks are pyroxene and amphibole andesites, tuffs and hydrothermally altered rhyolitic dacites, giving rise to copper, gold, lead and zinc mineralization.

Two volcanic stages have been identified in Tifraouine. The first stage began with an emission of volcanic ash and deposited a tuff layer a few metres thick, followed by an emission of lava and pyroclastic flows that formed pyroclastic breccias, while the second stage is characterized by an early and abundant emission of ash that created a volcanosedimentary formation with lava and coarse pyroclastic material and a formation of the Tifraouine calderas as the volcano collapsed, allowing the intrusion of andesitic and dacitic lava. All lavas in Tifraouine have petrographic characteristics of the calc-alkaline series (Benali, 2007).

Hydrothermal alterations are described by rocks exposed to different physical-chemical conditions at which they were originally formed reflecting new minerals by the actions of hydrothermal fluids (Woldai *et al*., 2010). In order to verify the presence of argillic, propylitic, sericitic and iron alterations on the surface around the caldera of Tifraouine, the observed alteration types on several levels are propylitization, expressed by calcite, epidote and chlorite; argilitization pronounced by kaolinite and illite; sericitization characterized by muscovite and oxidation described by iron oxides such as jarosite, hematite and goethite.

Following its formation, the Tifraouine volcano was affected by a series of tectonic accidents giving it a circular caldera structure with a diameter of 2.5 to 3 km, enclosing the Chadia wadi index. This caldera is itself contained within another concentric circular structure of 9 km in diameter that includes the Djebel Touila deposit (Belmouhoub, 1995). At the regional scale, Tifraouine is situated within the limits of littoral horst, characterized by secondary uplifts (in particular, Madakh uplift) and faults of various directions (Guardia, 1975). El Akehal Mountain is the tectonic framework of Tifraouine, located between the main faults of the region, where tectonic directions are NE-SW. In the Mesozoic bedrock of Tifraouine, two fault systems are nearly parallel to the main faults and major structural alignments of the Oran coastal area. The first series of NE-SW direction is at the origin of the general orientation of the anticline structures resumed in the form of horst. The N60ºE-N70ºE trending fault of El Akhal Mountain directed N60°- N70° is related to this system of faults. The second series is synchronous and perpendicular to the first. These are transversal faults in which the main outflows occur and set up two mineralized deposits (Touila Mountain and Wadi Chadia) (Fig. 3).

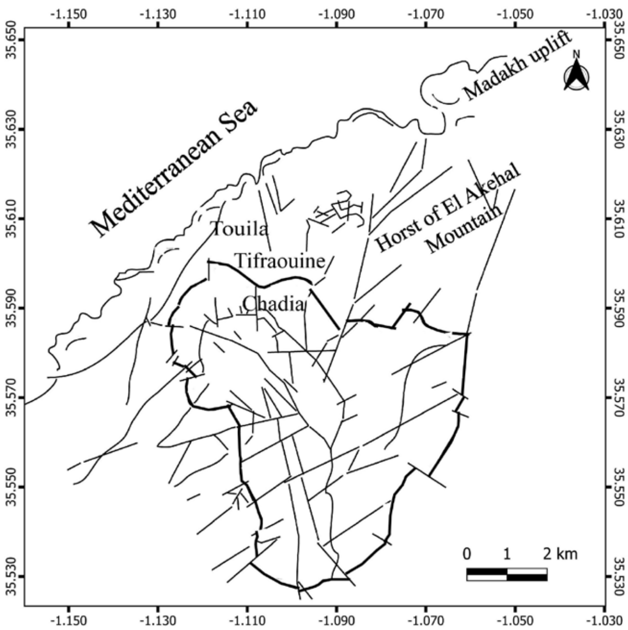

Fig. 3.- Structural map of Tifraouine (Belmouhoub, 1995).

Remote sensing and data analysis: Landsat 8 imagery

A cloud-free level 1T (terrain-corrected) Landsat 8/OLI/TIRS sensor imagery (path/row 198/35) of the Tifraouine area was downloaded from the (USGS) (http://earthexplorer.usgs.gov) in the TIFF format and projected to the WGS 84 datum in the Universal Transverse Mercator zone 30 North. The image used in this study was acquired by the satellite on 18 June 2013. For geological purposes, data collected in the visible and near-infrared (VNIR) and short-wave infrared (SWIR) bands are of principal interest (Frutuoso *et al*., 2021; Zanter, 2016). Seven of these nine bands are consistent with the Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+).

Geological mapping involved using typical absorption characteristics of chemical elements that compose minerals through spectral signatures in the spectral range (Pour and Hashim, 2015), that allows their detection and recognition. For example, montmorillonite shows absorptions around ~1413 nm and ~1911 nm, with the Al-OH features at ~2206 nm (Pontual *et al*., 2008; Clark *et al*., 1990), lower than ~1911 nm, and a slight inflection around ~1467 nm (Cardoso-Fernandes *et al*., 2022). Three bands can be effective in the mineral determination process. Band seven is the absorption band caused by clay mica, hydrous mineral, sulfates and some oxides. Band 6 refers to iron-rich or hematite rocks and is used in soil and rock discrimination. Band 4 is good in delineating soil cover and is used in the discrimination of soil from vegetation (Nait Amara *et al*., 2019).

Data preprocessing and methodology

The Landsat 8/OLI data of the study area were pre-processed and calibrated with ENVI software, by converting Landsat 8 calibrated digital numbers (DNs) to physical units; values of surface reflectance (SR) were obtained by the application of Fast Line of Sight Atmospheric Analysis of Hypercubes (FLAASH) algorithm of ENVI software (ENVI Tutorial, 2013). Hydrothermal alterations (clay, propylitic, iron and sericitisation) can be enhanced by using color composites (true color combination and false color combination images), band rationing (Sabin's ratio 5/6, 4/2 and 6/7) and spectral target detection tool by direct comparison with spectra of minerals in the spectral library. After these corrections, the resulting spectra can be compared directly with those of the spectral library (Scheidt, 2008).

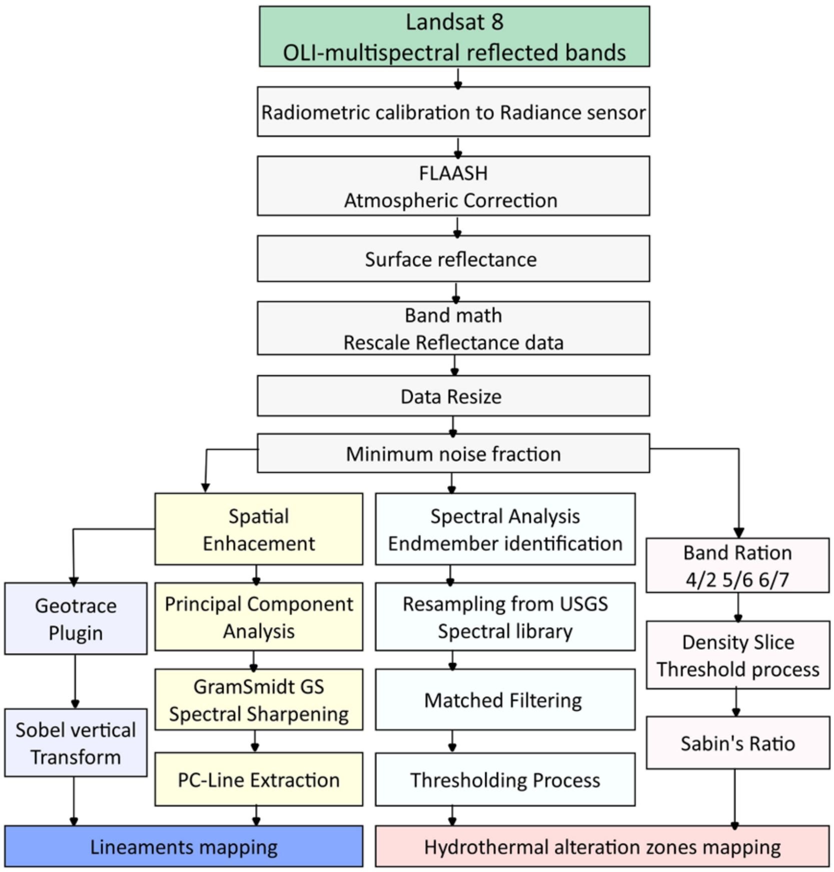

Fig. 4.- Workflow of Landsat 8 OLI data.

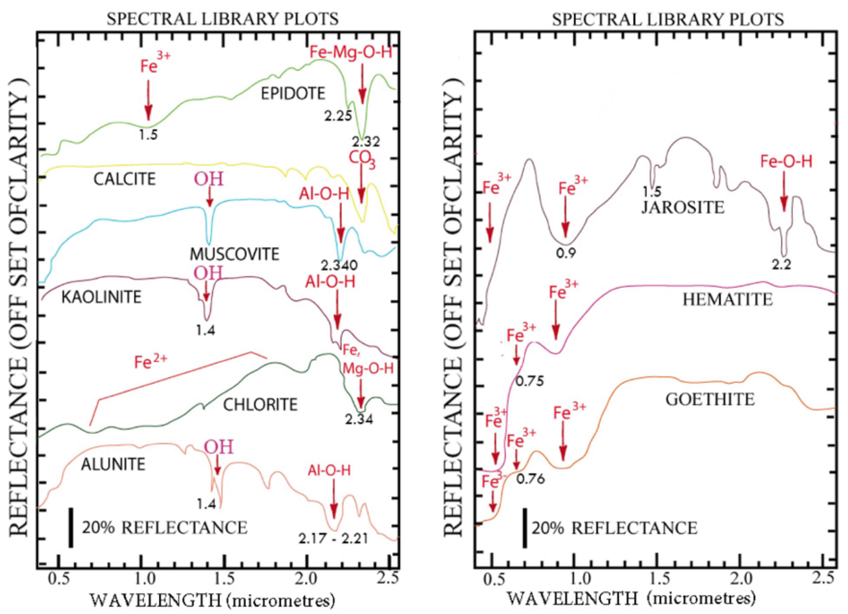

Fig. 5.- Laboratory spectra of the detected minerals used in the current study (Clark *et al*., 1993).

Minimum Noise Fraction (MNF) transformation was used to define the specific size of the data (Green *et al*., 1988). Band combination, band ratio, principal component analysis (PCA) and matched filtering (MF) were applied as image enhancement techniques. The preprocessing and processing schema used for Landsat 8 OLI data is summarized in a flow-chart (Fig. 4). A reflectance spectrum allows the discrimination of minerals as the optical spectrum of a mineral is directly related to its chemistry and crystallography (Turner *et al*., 2014). In the studied area, the clay alteration is represented by kaolinite with doublet absorption features at 2.165 and 2.200 µm. Illite has water absorption at 1.9 µm, 1.9 µm, Al-OH absorption characteristics at 2.20, ~2.34 and ~2.44 µm. Alunite has absorption features at ~2.17, 2.21 µm derived from Al-OH, and ~2.40 µm derived from S-O (Pontual *et al*., 2008; Fig. 5). Muscovite is a typical mineral in phyllic alteration, with distinct Al-OH absorption features at 2.20 µm and a less intense absorption features at 2.35µm. Chlorite, calcite and epidote are typical minerals of propylitic alteration, with absorption features of chlorite at 2.254 µm (Fe-OH) and (Mg-OH) absorption at 2.347µm (Fig. 5). Calcite has an absorption of C-O at ~2.345 µm which persist in mixtures (Fig. 5). Epidote has absorption features at ~1.545 µm that distinguishes it from chlorite and helps to identify epidote in mixtures (Fig. 5). Iron oxides such as jarosite having Fe–O–H absorption features at 0.94 and 2.27 µm (Hunt, 1977). Hematite is characterized by a peak at ~750 nm which gives it its distinctive red colour, weaker (Fe^{3+}) iron absorption at ~0.66 and 0.890 µm, derived from ferric iron. Goethite is characterized by a peak at ~0.76 µm which gives the distinctive red, orange colour to goethite, diagnostic ferric Fe^{3+} iron absorptions at ~0.66 nm and ~0.91 - 0.94 µm (Pontual *et al*., 2008).

The additional data used are geological and structural maps with an existing hydrothermal alteration map of Tifraouine Belmouhoub (2004) and Benali (2007). Three software packages that would process all steps analysis were used, in particular those of ENVI, QGIS and Geomatica. To extract hydrothermal alteration-related spectral and spatial data, the

Mapping hydrothermal alteration

Color composites

Tifraouine is characterized by average vegetation that is concentrated in the coastal zone and extends with the drainage system. For the identification of hydrothermal alteration minerals associated with the volcanic rocks of Tifraouine, green, red, blue (RGB) colour combination images and band ratios were created with the Landsat 8 OLI data spectral bands. The combination RGB 4, 3 and 2 is a representation of true color; the land cover nature is represented by the color combined images 5, 6 and 7.

Band ratio

Ratio is calculated by dividing the numerical value of a selected band by that of the other one which produces images of the relative band intensities; it is a technique known for highlighting certain features and materials that cannot be seen in raw bands (Inzana, 2003). They have been used for many years in the field of remote sensing to display spectral variations (Goetz *et al*., 1983), and also for reducing the topographic effect (Segal, 1983). Unique information may be extracted from band ratios, which would otherwise not be available from any single band. For this reason, these ratios have been successfully used to map altered areas (Jensen, 1996). In the current study, combination of RGB images called Sabin's ratio 5/6, 4/2 and 6/7 have been used to highlight iron oxides, clays and ferrous minerals (Sabins, 1999). The ratio 4/2 is useful for mapping iron oxides (hematite, goethite, jarosite, etc.) because they have absorption in the low blue region (band 2), while they have a high reflectance in the near red region (band 4). As they show high reflectance characteristics in band 5 and strong absorption features in band 6, ferrous minerals such as olivine, pyroxenes and amphiboles are mapped by the ratio 5/6 (Gupta, 2003, 2017). The ratio 6/7 was used for its capability to map kaolinite, montmorillonite (clay minerals), micas, alunite and talc–carbonates, etc. (Rowan *et al*., 1977; Goetz and Rowan, 1981; Frutuoso *et al*., 2021); all these minerals show high reflectance in band 6 and lower reflectance in band 7 of Landsat 8 OLI data. It enhances also vegetation (Agar and Coulter, 2007; Ducart *et al*., 2016).

Principal components analysis

PCA is widely applied to multispectral and hyperspectral remotely sensed data. It reduces data dimensionality (e.g., number of bands) and condenses the information in intercorrelated variables into a few variables (Jensen, 2005; Buenemann, 2011; Pour and Hashim, 2015). Usually, the first principal components PC1, PC2, PC3 containing the majority of information were selected for RGB display. This is the combination selected for interpretation.

Matched filtering

Supervised classifiers are usually applied to hyperspectral data but can also be applied to multispectral data. Therefore, maps of the mineral abundance can be produced. By this approach, data were analyzed to determine unique spectral end-members and their spatial distribution by producing detailed maps. This process requires several steps: spectral compression, noise removal by a linear transformation, MNF (Green *et al*., 1988) that consists of the following separate principal components analysis. The first rotation uses the principal components of the noise covariance matrix to decorrelate and rescale the noise in the data. The second rotation uses the principal components derived from the original image data after they have been noise whitened by the first rotation and rescaled by the noise standard deviation (Boardman *et al*., 1994). The MF method is described by Harsany and Chang (1994) and Boardman *et al*. (1998). This technique does not require knowledge of all the end-members within an image scene and can be used in the identification of single feature types. This method aims to identify individual minerals directly by target detection. To apply the MF algorithm, reference spectra must be selected from the spectral library or image collections and compared directly with the extracted spectra. It was applied to VNIR and SWIR bands of Landsat 8 OLI/TIRS data to map clays, sulfates, sericitic, propylitic mineral groups and Fe-oxides/hydroxides for each hydrothermal alteration mineral shown by automated identification and comparison with the spectral library. This is relatively insensitive to the magnitude of reflectance; therefore, the classification result is not affected by bidirectional reflectance effects or low to moderate shadowing. MF is able to quantitatively estimate the probability of a mineral occurrence and has been shown to result in excellent detectability and selectivity for spectrally distinct minerals (Boardman, 1998).

The MF algorithm equation is expressed as follows: $Fx = t - mTs - 1(x - m)$, where x represents the sampled vector, T concerns the targeted vector, m is the background mean and s the background covariance (Schott, 2007). This algorithm is the only one that could provide in such conditions semi-quantitative information (Van Der Meer and Steven, 2001; Santos *et al*., 2022). For the production of the distribution maps of the alteration minerals, the threshold processes are applied to the MF score (Fig. 6).

Structural elements and lineaments in Tifraouine

Several studies have revealed an important correlation between mineral deposits and lineaments, so the interpretation of lineaments and fractures is important in targeting ore deposits (Nait Amara, 2019; Cardoso-Fernandes, 2022). The tonal differences within the surface are reflected as direct lines on the satellite images that can be interpreted as visible lineaments (Zamyad *et al*., 2019). The dominant direction of lineaments in Tifraouine is NW-SE. It is related to the general orientation of the anticlinal structures resulting from the movements responsible for the formation of the coastal horst on a regional scale. To characterise and map lineaments in Tifraouine, it is necessary to extract the principal components (PC) and then choose the first principal component as it contains the most data information. Automatic lineament extraction from the PC1 Pansharpened band is performed with a PC-Line extractor in Geomatica software. The Geotrace plugin in QGIS provides and eases the identification of faults and fractures by using filters on Landsat 8 OLI data multispectral images, notably Sobel vertical transform. After this processing, the

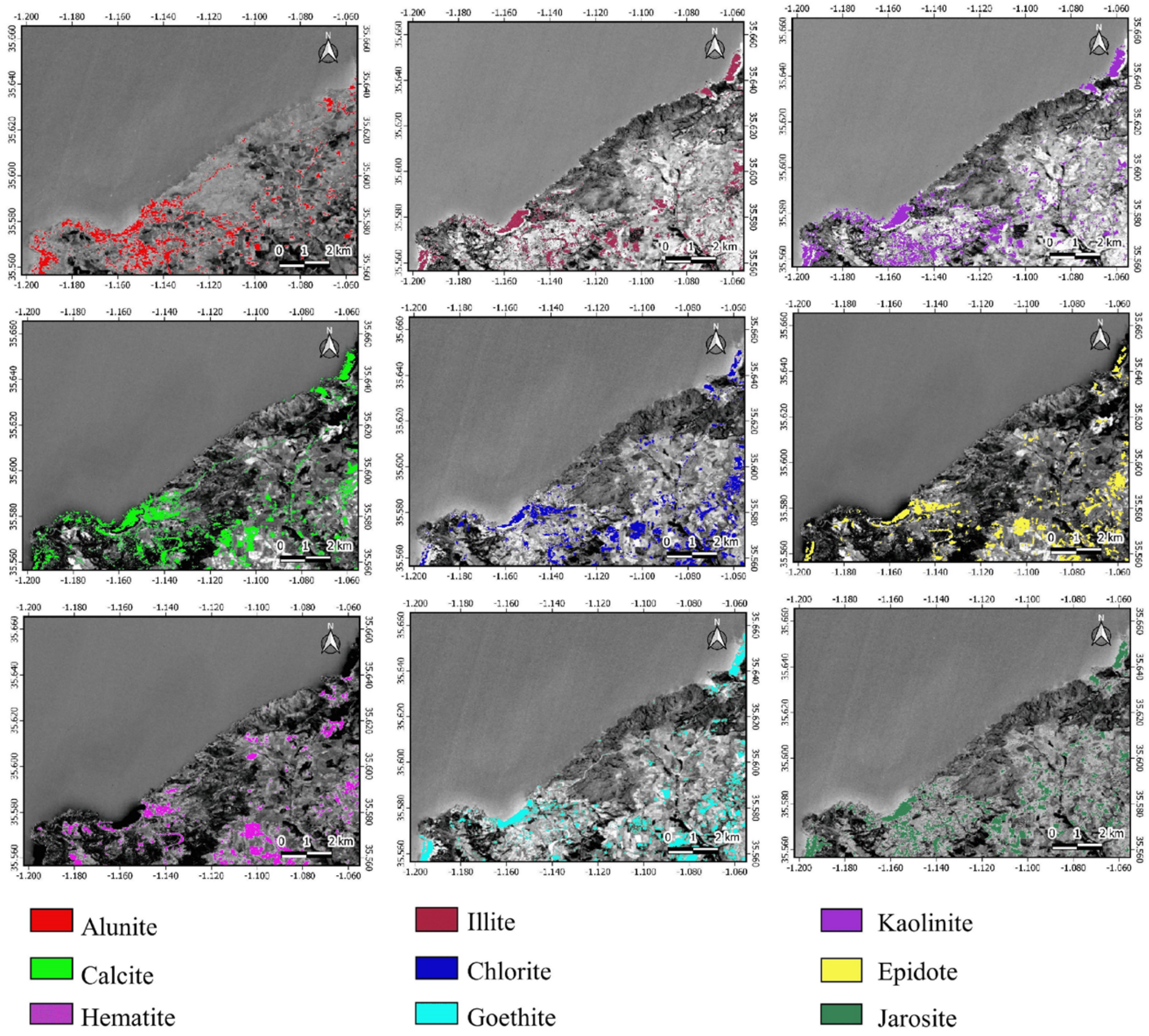

Fig. 6.- Mineral maps showing the results of MF method using Landsat 8 OLI data.

resulting lineaments were manipulated by Geographic Information System (GIS) software where the data were digitised, grouped and then mapped and statistically analysed to create rose diagrams for interpretation.

Results, discussion and validation

The intersection of lineament density with hydrothermal alteration zones is an indicator of mineralization (Rameshchandra, 2014). Results obtained from Landsat 8 satellite image processing techniques were compared to existing geological data including information about alteration, tectonic and lineaments of Tifraouine using GIS software. The combination RGB in Fig. 7A is a representation of true color and in Fig. 7B it shows rocks and soils in white and bluish pixels. The red and brownish area corresponds to natural and plantation vegetation.

Band rationing was used to create the False Colour Composite (FCC) image of 6/7, 6/5, 4/2 called Sabin's ratio. We obtain clays minerals (micas and talc–carbonate) in the bluish areas with vegetation in bright cyan pixels, iron oxides (hematite, goethite, and jarosite) in reddish areas and ferrous minerals in greenish areas (Fig. 8). The 6/7 ratio is commonly used to detect clays and vegetation (Da Cunha Frutuoso, 2015) because the spectra show high vegetation reflectance in the SWIR1 and low in the SWIR2 (Nait Amara *et al*., 2019). Therefore, it is expected that vegetation covering mineral deposits will have different reflectance curves than those growing in non-mineralized areas. The color patterns in the individual density-sliced images are different (Sabins, 1999). The use of the density slice option for each ratio in the ENVI by introducing threshold values, helps to highlight hydrothermal alterations (Fig. 9). The high-brightened areas show the potential target minerals (Cudahy *et al*., 2008; Rockwell, 2013; Eldosouky *et al*., 2017). Stages of mapping alterations by ratio bands are shown in Fig 10 as a flow chart and results are shown in Fig. 11. The PCA results in Fig. 12 show the ferrous minerals in light green and the iron oxides in greenish yellow pixels.

As shown in Fig. 13, mapped and collected lineaments are mainly distributed along the NE-SW direction which is

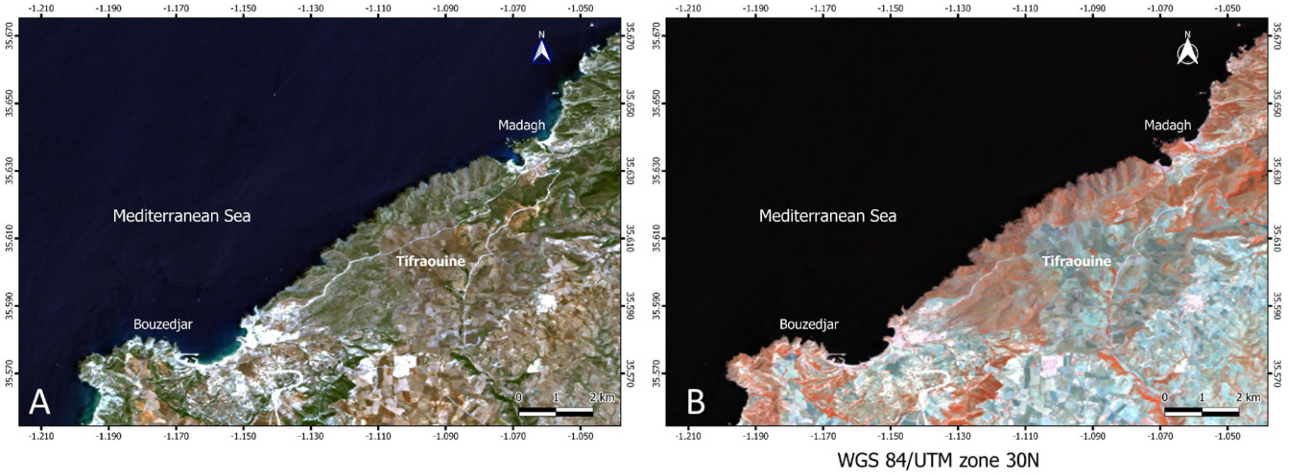

Fig. 7.- Composite color maps. A) True color image RGB combination of bands 4, 3, and 2. B) RGB combination of bands 5, 6, and 7.

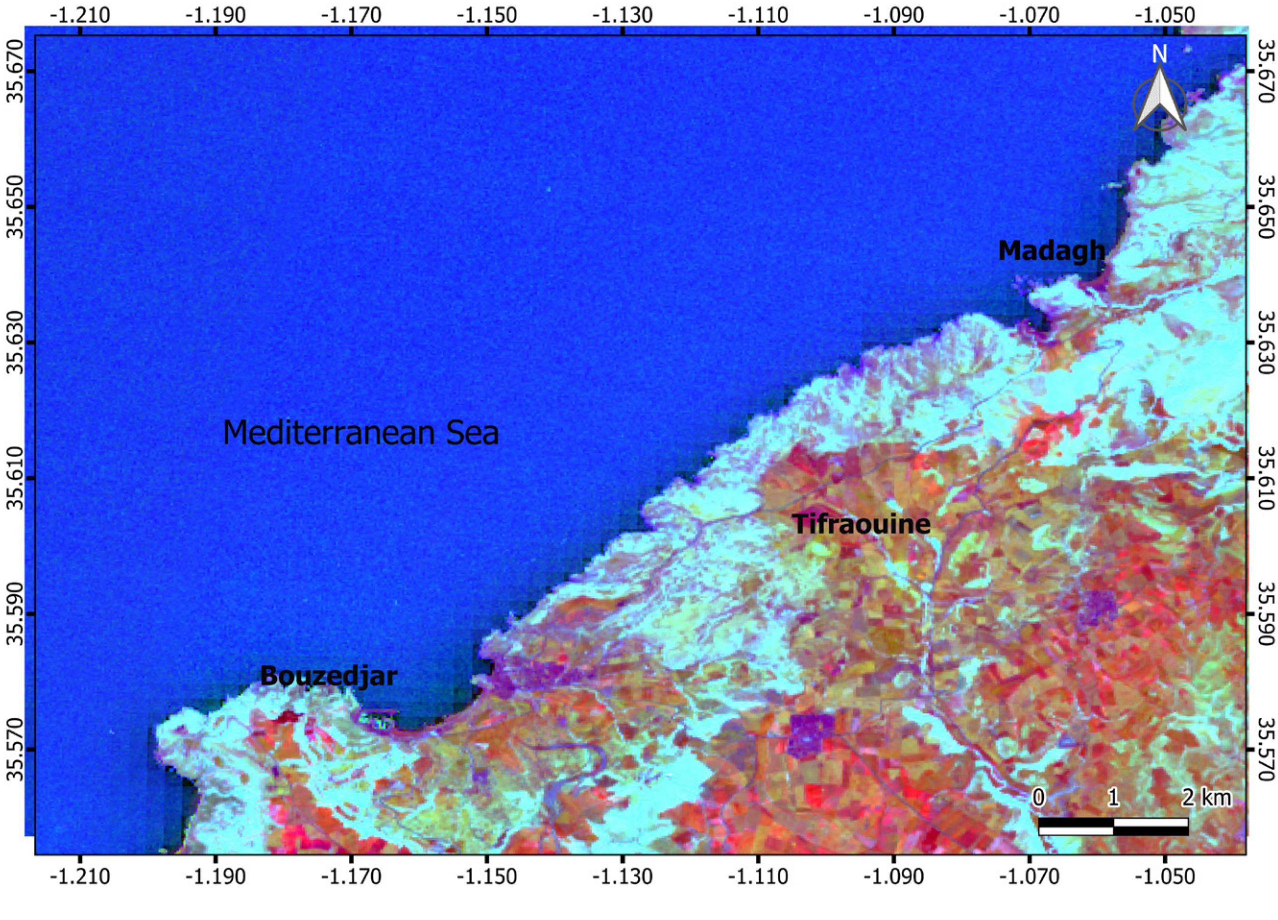

Fig. 8.-Combination of 6/7, 5/6, 4/2 in RGB composition image reveals the alteration areas in bright cyan and bright pink color.

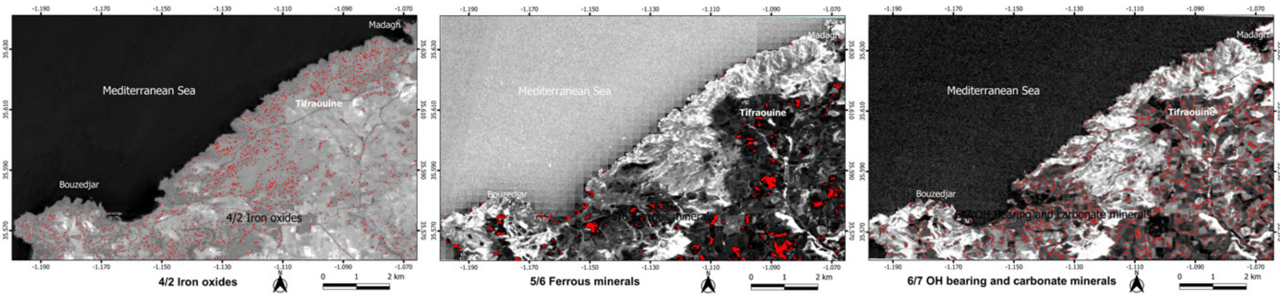

Fig. 9.-Hydrothermal alterations of each ratio using density slicing by introducing threshold values. From left to right: 4/2 iron oxides, 5/6 ferrous minerals, and 6/7 OH bearing and carbonate minerals.

effectively the direction of the major faults of Tifraouine and the most predominant ones corresponding globally to the orientation of the entire region and correspond to what was revealed by the field studies. Through remote sensing, other faults of NW-SE direction have been identified, in addition to some W-E transverse faults, probably those along which the main flows occurred in relation to the mineral deposits of Touila and Chadia. The large caldera of Tifraouine has been identified, including another circular structure representing a second caldera. They are pierced by several fractures that occurred after the formation of the Tifraouine volcano, notably on its NW side. Due to the density of accidents in this part of the caldera, the interaction of hydrothermal fluids along the fractures carrying the mineralizing fluids is important, therefore this zone is probably rich in mineralizations. Results of matched filtering method and band rationing applied to OLI/Landsat 8 data were superimposed on the existing lineaments to create one representative figure of the four types of alteration; this figure shows a spatial distribution of alterations between the two regions Tifraouine and Bouzedjar region (Fig. 14). The comparison of the results obtained by remote sensing and those of the field studies reveals that alterations extend from the Tifraouine calderas to the Bouzedjar area. The clay alteration occurs near the caldera and extends towards the Bouzedjar area through faults and fractures. Sericitic alteration is represented by muscovite and is more extensive. Iron alteration is represented by goethite, haematite and jarosite and shows a broad distribution in the studied areas. Propylitic alteration is the most abundant type of alteration and is observed in more areas (Fig. 14). There is a similarity between the results obtained by the field studies and those we have obtained by remote sensing. The combination of lithological information, structural, and the hydrothermally altered areas defines a new exploration targets (promising zones of mineralization). Thus, the detail obtained in this study allows to extend the study area towards the western side of Bouzedjar to better understand the evolution of these alterations. For more detail and accuracy, the area needs to be further explored with more field studies and taking into account the structural factor that plays a major role in the migration of hydrothermal fluids carrying mineralization.

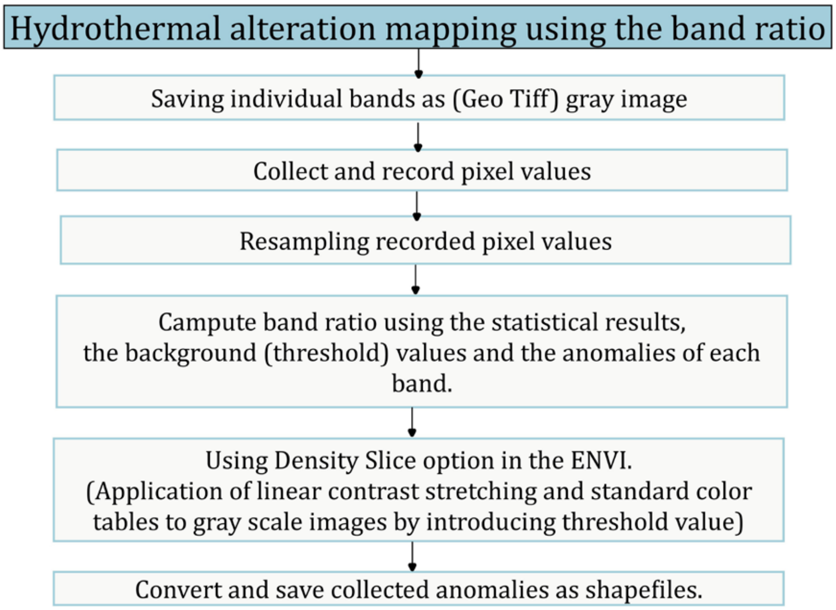

Fig. 10.-Flowchart of hydrothermal alteration mapping steps by band ratios.

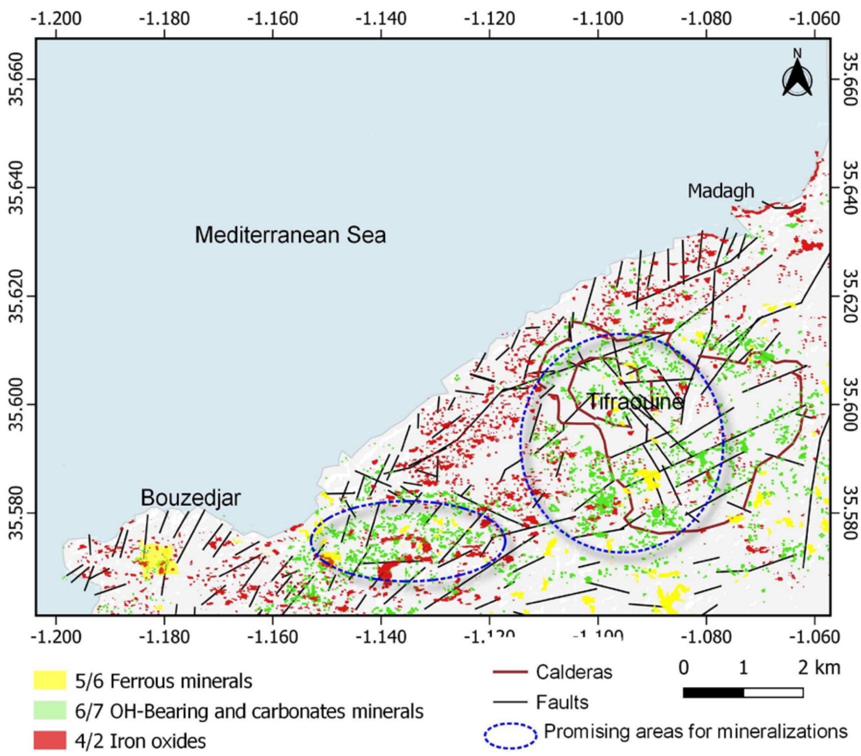

Fig. 11.- Mapping of hydrothermal alteration by ratio bands. Superimposition of the three ratios results.

Conclusion

In this study, we have provided a new distribution map of alteration in Tifraouine for each type of clay, propylitic, iron and sericitic alteration selected to be detected by remote sensing to enhance potential mining exploration areas, especially those related to hydrothermal activity in Tifraouine and Bouzedjar. The specific band ratio (Sabin's) highlights clay and iron alteration and thus shows that clays are abundant in Tifraouine and Bouzedjar, also concentrated throughout the water flow system, as well as in faults and fractures. All results were pooled and mapped to identify four representative maps for each type of alteration (clay, propylitic, sericite and iron). Direct detection by MF has been applied to SWIR and VNIR bands of Landsat 8 data to verify the results of previous methods, providing clearer and more accurate information on the detection and distribution of alteration minerals, and confirming previous findings that mineralization is concentrated around the caldera of Tifraouine and in the western sector namely Bouzedjar. Maps obtained from processed Landsat 8 OLI satellite images, through the integration of hydrothermal alteration zones in the GIS with previous studies; show that the Tifraouine and Bouzedjar areas have significant mining potential. From the results obtained by various processing and mapping methods, as well as after superimposing the distribution of hydrothermal alterations on the mapped lineaments and the pre-existent volcanic formations, it can be deduced that hydrothermal alterations are controlled by volcanism and the typical structural features in Tifraouine. The processing of Landsat 8 images has allowed the highlighting of hydrothermal alterations and some structural features in Tifraouine, which proves the existence of these hydrothermally altered minerals as previously shown by the field studies. Nevertheless, it is very evident that the use of higher-resolution images will enable better precision and enhancement of the results and this will be the objective of the next studies in this region.

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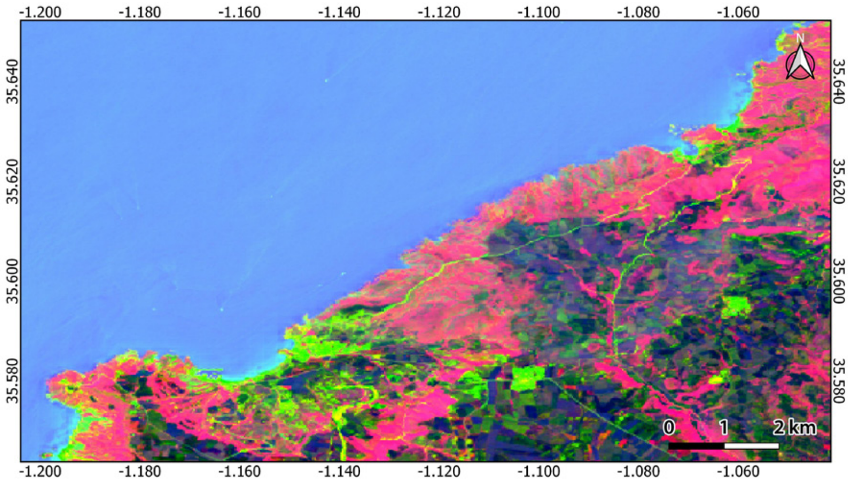

Fig. 12.- RGB color combination of PC1, PC2, and PC3, showing the results of PCA. PC1 in the blue channel, PC2 in the green channel and PC3 in the red channel.

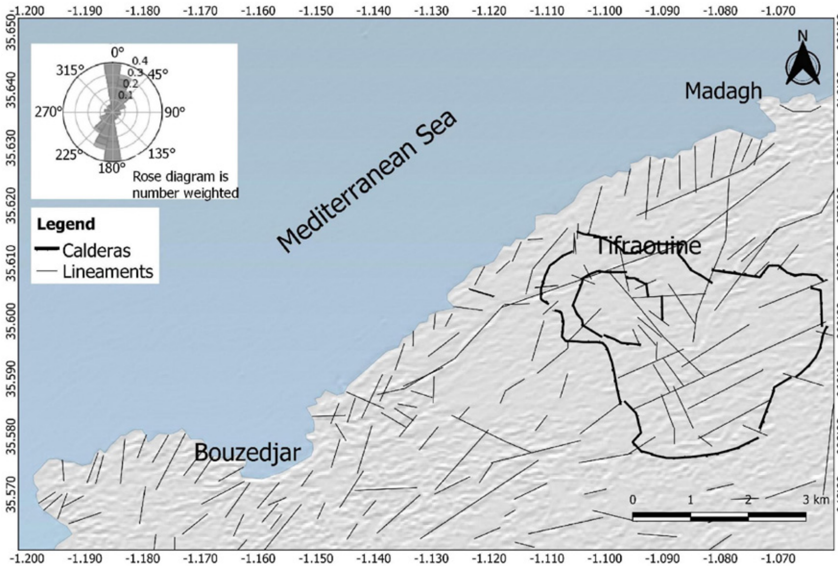

Fig. 13.- Lineament extraction in Tifraouine using the first principal component and PC-Line extractor.

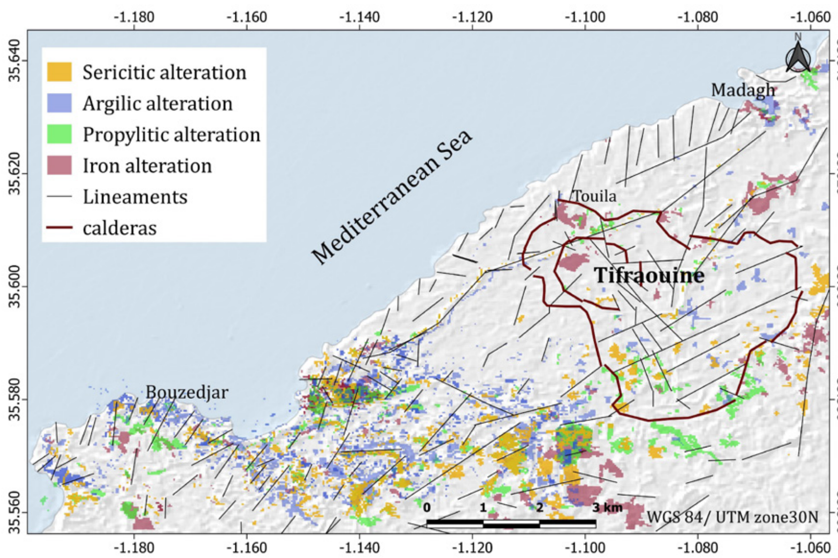

Fig. 14.- Distribution map of hydrothermal alterations in Tifraouine.

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Author contributions

The individual contribution of each author and elaboration to the work: manuscript preparation, B.L., H.B.; methodology, B.L., H.B., A.B.; data curation, B.L., K.M.; data processing, B.L., K.M.; figures, H.B., K.M., A.B.; research/analysis, B.L., H.B.; manuscript review, H.B., B.L., A.B.; coordination, H.B.; supervision, B.L.

References

Abdelnasser, A., Kumral, M., Zoheir, B., Karaman, M., Weihed, P., 2018. REE geochemical characteristics and satellite-based mapping of hydrothermal alteration in Atud gold deposit. Egypt. Journal of African Earth Sciences, 145: 317-330.

Adiri, Z., Lhissou, R., El Harti, A., Jellouli, A., Chakouri, M., 2020. Recent advances in the use of public domain satellite imagery for mineral exploration: A review of Landsat-8 and Sentinel-2 applications. Ore Geology Reviews, 117: 103332. https://doi.org/10.1016/j.oregeorev.2020.103332

Agar, B., Coulter, D., 2007. Remote sensing for mineral exploration a decade perspective 1997-2007. In: Milkereit B (ed) Proceedings of Exploration 07. Fifth Decennial International Conference on mineral Exploration, 109-136.

Ali, A., Pour, A., 2014. Lithological Mapping and Hydrothermal Alteration Using Landsat 8 Data: A Case Study in Ariab Mining District, Red Sea Hills, Sudan. International Journal of Basic and Applied Sciences, 3, 199-208. https://doi.org/10.14419/ijbas.v3i3.2821

Amin Beiranvand, P., Mazlan, H., 2014. Hydrothermal alteration mapping from Landsat 8 data, SarCheshmeh copper mining district, south-eastern Islamic Republic of Iran. Journal of Taibah University for Science 9 (2015) 155-166. https://doi.org/10.1016/j.jtusci.2014.11.008

Azizi, H., Rsaouli, A.A., Babaei, K., 2007. Using SWIR bands from ASTER for discrimination of hydrothermal altered minerals in the Northwest of Iran (SE-Sanandaj City): a key for exploration of copper and gold mineralisation. Research Journal of Applied Sciences, 2 (96): 763-768. https://medwelljournals.com/abstract/?doi=rjasci.2007.763.768

Beane, R.E., 1982. Hydrothermal alteration in silicate rocks, southwestern North America, in Titley, S.R., ed., Advances in geology of the porphyry copper deposits: Univ. Arizona Press, Tucson, 117-137.

Belmouhoub, A., 1995. Rapport sur l'évaluation géochimique de la potentialité de quelques manifestations ferrugineuses du massif de M'Sirda (Algérie Nord-Occidentale). Rapport de fin de cycle C.E.S.E.V, Nancy, 46 p.

Belmouhoub, A., 2004. Les minéralisations sulfurées à Cu, (Au), Pb-Zn associées aux roches volcaniques miocènes du massif de Tifferaouine (Sahel oranais): Pétrographie, géochimie et prospection minière. Magister thesis, U.S.T.H.B, Algiers, 130 p.

Benali, H., 2007. Les minéralisations associées aux roches magmatiques tertiaires du Nord de l'Algérie: Typologie, pétrologie, cadre géodynamique et implications métallogéniques. Thèse de doctorat, U. S. T. H. B, Alger, 173 p.

Boardman, J.W., 1998. Leveraging the high dimensionality of AVIRIS data for improved subpixel target unmixing and rejection of false positives: mixture tuned matched filtering. In: Pasadena, CA. Summaries of the Seventh Annual JPL Airborne Geoscience Workshop, 6.

Boardman, J.W., Kruse, F.A., 1994. Automated spectral analysis: a geological example using AVIRIS data, north Grapevine Mountains, Nevada. Tenth Thematic Conference on Geologic Remote Sensing, Environmental Research Institute of Michigan: 1407-1418.

Buenemann, M., Martius, C., Jones, J.W., Herrmann, S.M., Klein, D., Mulligan, M., Reed, M.S., Winslow, M., Washington-Allen, R.A., Lal, R., Ojima, D., 2011. Integrative geospatial approaches for the comprehensive monitoring and assessment of land management sustainability: Rationale, Potentials, and Characteristics. Land degradation and development, 22 (2): 226-239. https://doi.org/10.1002/ldr.1074

Cardoso-Fernandes, J., Teodoro, A., Alexandre, L., 2019. Remote sensing data in lithium (Li) exploration: A new approach for the detection of Li-bearing pegmatites. International Journal of Applied Earth Observation and Geoinformation, 76: 10-25. https://doi.org/10.1016/j.jag.2018.11.001

Cardoso-Fernandes, J., Teodoro, A.C., Lima, A., Menuge, J., Brönner, M., Steiner, R., 2022. Sentinel-1 and ALOS data for lineament extraction: a comparative study. Earth Resources and Environmental Remote Sensing/GIS Applications XIII, Berlin, Germany, 122680X. https://doi.org/10.1117/12.2636117

Ciszak, R., 1993. Evolution géodynamique de la chaîne tellienne en Oranie (Algérie occidentale) pendant le Paléozoique et le Mésozoique. Thèse de doctorat, Univ. Toulouse, 513 p.

Clark, R.N., King, T.V.V., Klejwa, M., Swayze, G.A., Vergo, N., 1990. High spectral resolution reflectance spectroscopy of minerals. Journal of Geophysical Research: Solid Earth, 95: 12653-12680. https://doi.org/10.1029/JB095iB08p12653

Clark, R.N., Swayze, G.A., Gallagher, A., King, T.V.V., Calvin, W.M., 1993. The U.S. Geological Survey, digital spectral library: version 1: 0.2 to 3.0 microns. U.S. Geological Survey Open File Report: 93-592. https://doi.org/10.3133/ofr93592

Cudahy, T., Jones, M., Thomas, M., Laukamp, C., Caccetta, M., Hewson, R., Verrall, M., 2008. Next generation mineral mapping in Queensland: another piece to the precompetitive geoscience data puzzle, Australian Earth Sciences Convention (AESC): 20-24.

Da Cunha Frutuoso, R.M., 2015. Mapping hydrothermal gold mineralization using Landsat 8 data. A case of study in Chaves license, Master thesis, Univ. Porto, Portugal, 85 p.

Ducart, D.F., Silva, A.M., Toledo, C.L.B., Assis, L.M.D., 2016. Mapping iron oxides with Landsat-8/OLI and EO-1/Hyperion imagery from the Serra Norte iron deposits in the Carajás Mineral Province, Brazil. Brazilian Journal of Geology, 46 (3): 331-349. https://doi.org/10.1590/2317-4889201620160023

Eisele, A., Lau, I., Hewson, R., Carter, D., Wheaton, B., Ong, C., Kaufmann, H., 2012. Applicability of the thermal infrared spectral region for the prediction of soil properties across semi-arid agricultural landscapes. Remote Sensing, 4 (11): 3265-3286. https://doi.org/10.3390/rs4113265

Eldosouky, A.M., Abdelkareem, M., Elkhateeb, S.O., 2017. Integration of remote sensing and aeromagnetic data for mapping structural features and hydrothermal alteration zones in Wadi Allaqi area, South Eastern Desert of Egypt. Journal of African Earth Sciences, 130: 28-37. https://doi.org/10.1016/j.jafrearsci.2017.03.006

ENVI Tutorial., 2013. Exelis visual information solutions. Boulder, Colorado.

Fenet, B., 1975. Recherches sur l'alpinisation de la bordure septentrionale du bouclier africain à partir de l'étude d'un élément de l'orogène nord maghrébin, les monts de Djebel Tessala et les massifs du littoral oranais. Thèse de doctorat, Univ. Nice, 301 p.

Frutuoso, R., Lima, A., Teodoro, A.C., 2021. Application of remote sensing data in gold exploration: targeting hydrothermal alteration using Landsat 8 imagery in northern Portugal. Arabian Journal of Geosciences, 14: 1-18. https://doi.org/10.1007/s12517-021-06786-0

Glaçon, J., 1967. Recherches sur la géologie et les gîtes métallifères du Tell sétifien (Algérie). Publications du Service géologique de l'Algérie, nouvelle série, Bulletin, no. 32.

Goetz, A.F., Rock, F., Hand Rowan, B.N., 1983. Remote sensing for exploration, an overview. Economic Geology, 78: 573-590. https://doi.org/10.2113/gsecongeo.78.4.573

Green, A.A., Berman, M., Switzer, P., Craig, M. D., 1988. A transformation for ordering multispectral data in terms of image quality with implications for noise removal. IEEE Transactions on Geoscience and Remote Sensing, 26 (1): 65-74. https://doi.org/10.1109/36.3001

Guardia, P., 1975. Géodynamique de la marge alpine du continent africain d'après l'étude de l'Oranie Nord Occidentale. Relations structurales et paléogéographiques entre le Rif externe: le Tell et L'avant-pays atlasique. Univ. Nice, 286 p.

Gupta, R.P., 2003. Remote sensing geology. Springer Berlin, Heidelberg, 428 p. https://doi.org/10.1007/978-3-662-05283-9

Gupta, R.P., 2017. Remote sensing geology. Springer. https://doi.org/10.1007/978-3-662-55876-8

Harsanyi, J.C., Chang, C.I., 1994. Hyperspectral image classification and dimensionality reduction: An orthogonal subspace projection approach. IEEE Transactions on Geoscience and Remote Sensing, 32: 779-785. https://doi.org/10.1109/36.298007

Himri, Y., Boudghene Stambouli, A., Draoui, B., Himri, S., 2008. An investigation on wind power potential in Tindouf region Algeria. Proceedings of world academy of science, engineering and technology, 33 (7): 1128-1136. https://doi.org/10.1016/j.rser.2008.09.007

http://earthexplorer.usgs.gov [Consulted on 17 March 2014].

https://landsat.gsfc.nasa.gov [Consulted on 10/06/2014].

Hu, B., Xu, Y., Wan, B., Wu, X., Yi., G., 2018. Hydrothermally altered mineral mapping using synthetic application of Sentinel-2A MSI, ASTER and Hyperion data in the Duolong area, Tibetan Plateau, China. Ore Geology Reviews, 101: 384-397. https://doi.org/10.1016/j.oregeorev.2018.07.017

Hunt, G.R., 1977. Spectral signatures of particulate minerals in the visible and near infrared, Geophysics, 42: 501-513. https://doi.org/10.1190/1.1440721

Ibrahima, E., Barnabéa, P., Ramanaidoub, E., Pirarda, E., 2018. Mapping mineral chemistry of a lateritic outcrop in new Caledonia through generalized regression using Sentinel-2 andfield reflectance spectra. International Journal of Applied Earth Observation and Geoinformation, 73: 653-665. https://doi.org/10.1016/j.jag.2018.08.004

Inzana, J., Kusky, T., Higgs, G., Tucker, R., 2003. Supervised classifications of Landsat TM band ratio images and Landsat TM band ratio image with radar for geological interpretations of central Madagascar. Journal of African Earth Sciences, 37: 59-72. https://doi.org/10.1016/S0899-5362(03)00071-X

Jensen, J.R., 1996. Introducing digital image processing: A remote sensing perspective; 2nd, Prentice Hall Series in geographic information Siences. l'Université du Michigan, 318 p.

Jensen, J.R., 2005. Introductory Digital Image Processing: A Remote Sensing Perspective. 3rd Edition, Prentice Hall, Upper Saddle River. l'Université de Californie, 526 p.

Megartsi, M., 1985. Le volcanisme Mio-Plio-quaternaire de l'Oranie nord occidentale, 296 p.

Mia, B., Fujimitsu, Y., 2012. Mapping hydrothermal altered mineral deposits using Landsat 7 ETM+ image in and around Kuju volcano, Kyushu, Japan. Journal of Earth System Science, 121 (4): 1049- 1057. https://doi.org/10.1007/s12040-012-0211-9

Mina, Z., Peyman, A., Reza, N., 2019. Determination of Hydrothermal Alteration Zones Using Remote Sensing Methodes in Tirka Area, Toroud, NE Iran. Journal of the Indian Society of Remote Sensing, 47: 1817-1830. https://doi.org/10.1007/s12524-019-01032-3

Mouffok, K., Boukhechba, M., 1999. Contibution à l'étude petrographique et gîtologique du massif de Tifferaouine (Sondage TS 15). Mémoire d'ingéniorat d'état, USTHB, 157 p.

Mwaniki, M.W., Moeller, M.S., Schellmann, G., 2015. A comparison of Landsat-8 (OLI) and Landsat-7 (ETM+) in mapping geology and visualising lineaments: a case study of central region Kenya. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 7 (W3): 897-903. https://doi.org/10.5194/isprsarchives-XL-7-W3-897-2015

Nait Amara, B., Aissa, D.E., Maouche, S., Braham, M., Machane, D., Guessoum, N., 2019. Hydrothermal alteration mapping and structural features in the Guelma basin (Northeastern Algeria): contribution of Landsat-8 data. Arabian Journal of Geosciences, 12, 94. https://doi.org/10.1007/s12517-019-4224-4

Ninomiya, Y., 2003. A stabilized vegetation index and several mineralogic indices defined for ASTER VNIR and SWIR data. In Geoscience and Remote Sensing Symposium, 2003. IGARSS'03. Proceedings, 3: 1552-1554.

O'Leary, D.W., Friedman, J.D., Pohn, H.A., 1976. Lineament, Linear, Lineation: Some proposed new standard for old terms. Geological Society of America Bulletin, 87: 1463-1469. https://doi.org/10.1130/0016-7606(1976)87<1463:LLLSPN>2.0.CO;2

Peleli, S., Kouli, M., Marchese, F., Lacava, T., Vallianatos, F., Tramutoli, V., 2021. Monitoring temporal variations in the geothermal activity of Miocene Lesvos volcanic field using remote sensing techniques and MODIS – LST imagery, International Journal of Applied Earth Observation and Geoinformation, 95. https://doi.org/10.1016/j.jag.2020.102251

Pique, A., Brahim, L.A., Ouali, R.A., Amrhar, M., Charroud, M., Gourmelen, C., Tricart, P., 1998. Evolution structurale des domaines atlasiques du Maghreb au Méso-Cénozoïque; le rôle des structures héritées dans la déformation du domaine atlasique de l'Afrique du Nord. Bulletin de la Société Géologique de France, 169 (6): 797-810.

Pontual, S., Merry, N., Gamson, P., 2008. Spectral Analysis Guides for Mineral Exploration. Ausspec International Ltd, Victoria, 189 p.

Pour, A., Hashim, M., 2015. Hydrothermal alteration mapping from Landsat-8 data, Sar Chesmeh copper mining district, south-eastern Islamic Republic of Iran. Journal of Taibah University for Science, 9: 155-166. https://doi.org/10.1016/j.jtusci.2014.11.008

Pour, A.B., Hashim, M., Genderen, J.V., 2013. Detection of hydro- thermal alteration zones in a tropical region using satellite remote sensing data: Bau goldfield, Sarawak, Malaysia, Ore Geology Reviews, 54: 181–196. https://doi.org/10.1016/j.oregeorev.2013.03.010
Rameshchandra, P., 2014. A gis based correlation between lineaments and gold occurences of ramagiri-penakacherlaschist belt, Eastern Dharwar craton, India. International Journal of Geology, Earth and Environmental Sciences, (4): 259-267.
Rockwell, B.W., 2013. Automated mapping of mineral groups and green vegetation from Landsat Thematic Mapper imagery with an example from the San Juan Mountains, Colorado. Scientific Investigations Map, 3252. https://doi.org/10.3133/sim3252
Rowan, L.C., Goetz, A.F.H., Ashley, R.P., 1977. Discrimination of hydrothermally altered and unaltered rocks in visible and near infrared multispectral images. Geophysics, 42 (3): 522-535. https://doi.org/10.1190/1.1440723
Sabins, F.F., 1999. Remote sensing for mineral exploration. Ore Geology Reviews, 14 (3-4): 157-183. https://doi.org/10.1016/S0169-1368(99)00007-4
Santos, D., Cardoso-Fernandes, J., Lima, A., Teodoro, A. C., 2022. The potential of spectral unmixing method applied to PRISMA hyperspectral images in the identification of Li minerals: an evaluation for prospecting purposes. Paper presented at the SPIE Remote Sensing, Earth Resources and Environmental Remote Sensing /GIS Applications XIII, Berlin, Germany. https://doi.org/10.1117/12.2636034
Scheidt, S., Ramsey, M., Lancaster, N., 2008. Radiometric normalization and image mosaic generation of ASTER thermal infrared data: an application to extensive sand and dune fields. Remote Sensing of Environment, 112: 920-933. https://doi.org/10.1016/j.rse.2007.06.020
Schott, J.R., E.B., 2007. Remote Sensing: The Image Chain Approach, second ed. Oxford University Press, New York, 688 p.
Segal, D.B., 1983. Use of Landsat multispectral scanner data for definition of limonitic exposure in heavily vegetated areas, El Raso Texas, Economic Geology, 78 (4): 711-722. https://doi.org/10.2113/gsecongeo.78.4.711
Souhalia, A., 2001. Contribution à l'étude pétrographique et gîtologique du massif de Tifferaouine (Sondage T22). Mémoire d'ingéniorat d'état, USTHB, 87 p.
Torres-Vera, M.A., Prol-Ledesma, R.M., 2003. Spectral enhancement of selected pixels in thematic mapper images of the Guanajuato district (Mexico) to identify hydrothermally altered rocks. International Journal of Remote Sensing, 24 (22): 4357-4373. https://doi.org/10.1080/0143116031000075134
Turner, DJ., Rivard, B., Groat, LA., 2014. Visible and short-wave infrared reflectance spectroscopy of REE phosphate minerals. American Mineralogist, 99: 1335-1346. https://doi.org/10.2138/am.2014.4674
Van der Meer, F.D., Van derWerff, H.M.A., Van Ruitenbeek, F.J.A., Hecker, C.A., Bakker, W.H., Noomen, M.F., Woldai, T., 2012. Multi- and hyperspectral geologic remote sensing: a review. International Journal of Applied Earth Observation and Geoinformation, 14 (1): 112-128. https://doi.org/10.1016/j.jag.2011.08.002
Wang, G., Du, W., Carranza, E.J.M., 2017. Remote sensing and GIS prospectivity mapping for magmatic-hydrothermal base- and precious-metal deposits in the Honghai district, China. Journal of African Earth Sciences, 128: 97-115. https://doi.org/10.1016/J.JAFREARSCI.2016.06.020
Woldai, T., Amera, S.A, Carranza, E.J.M., Jemwa, G., Duke, E.F., 2010. Spectral remote sensing of hydrothermal alteration associated with volcanogenic massive sulphide deposits, Gorob-Hope Area, Namibia. 8th International AARSE Conference, Addis Ababa, Ethiopia, 25-29.
Yousefi, M., Tabatabaei, S.H., Rikhtehgaran, R., Pour, A.B., Pradhan, B., 2021. Application of Dirichlet Process and Support Vector Machine Techniques for Mapping Alteration Zones Associated with Porphyry Copper Deposit Using ASTER Remote Sensing Imagery. Minerals, 11 (11): 1-25. https://doi.org/10.3390/min11111235
Zanter, K., 2016. Landsat 8 (L8) Data Users Handbook. Department of the Interior U.S. Geological Survey, South Dakota, 106 p.

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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*

Aoulad-Sidi-Mhend, A., Martín-Martín, M., Hlila, R., Maaté, A., Chakiri, S., Achab, M., Aziz, A., Slimani, H., Maaté, S., Mohammadi, M., 2023. Methodology for a Moroccan inventory and assessment of geological sites: a proposal to be applied in other African regions. *Revista de la Sociedad Geológica de España*, 36 (1): 16-37.

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-

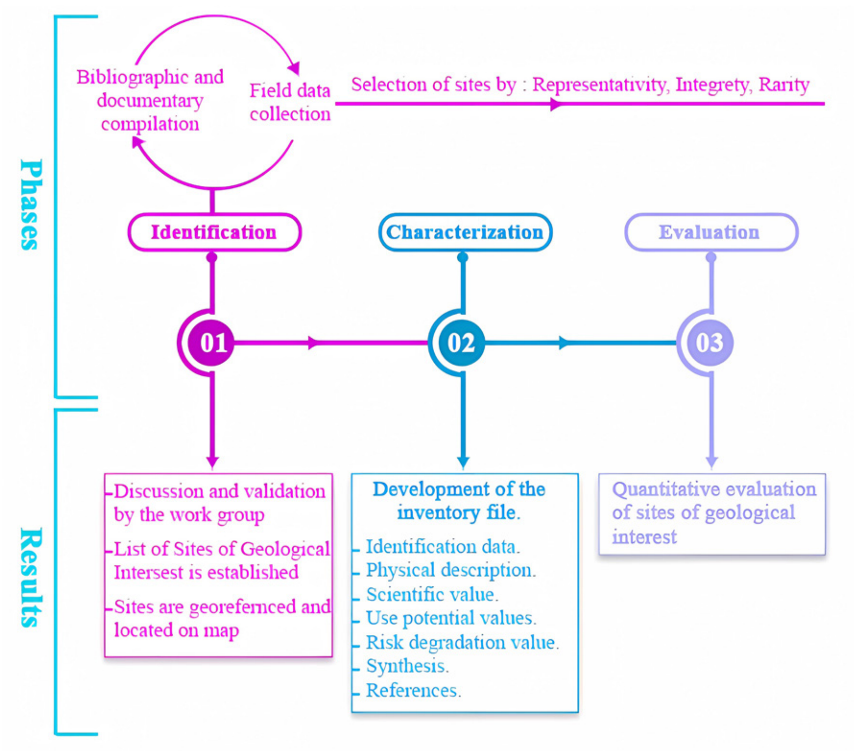

Fig. 1.- Methodology of the inventory of Sites of Geological Interest (SGIs).

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-

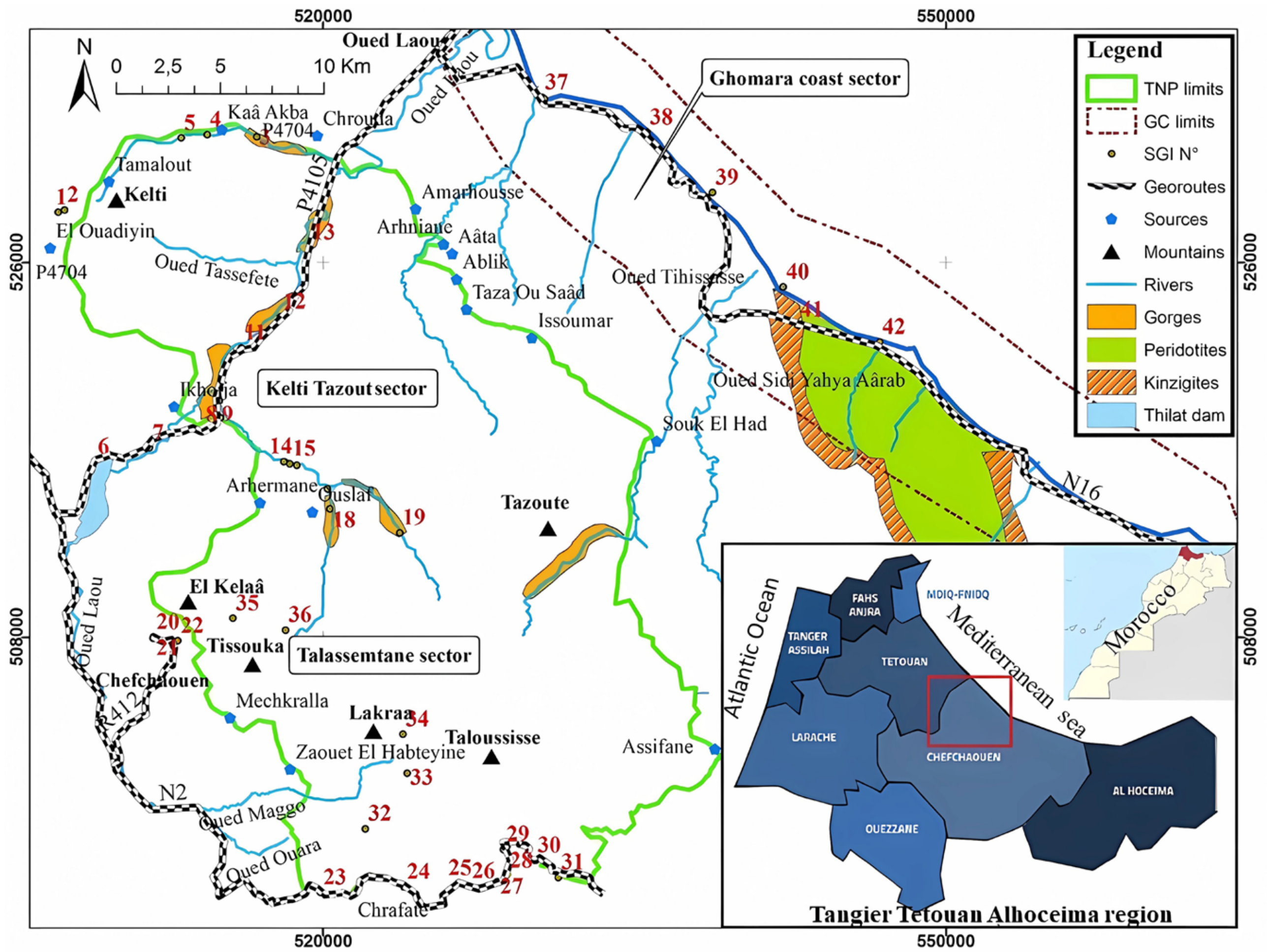

Fig. 2.- Sketch map of the study area, with the SGIs (red numbers) analyzed within the Talassemtane National Park and the Ghomara Coast (TNP-GC) area and its location in Northern Morocco (lower-right box).

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

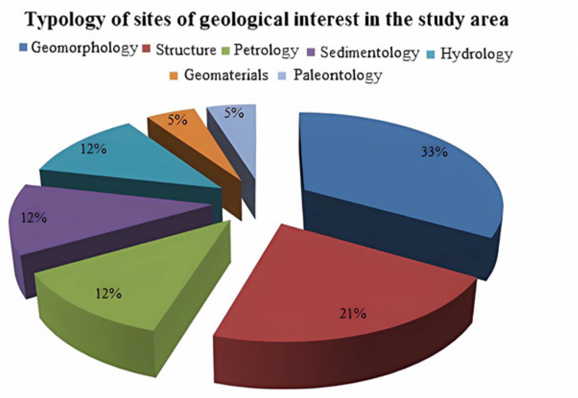

Fig. 3.- Average of the SGI typologies in the TNP-GC area.

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.

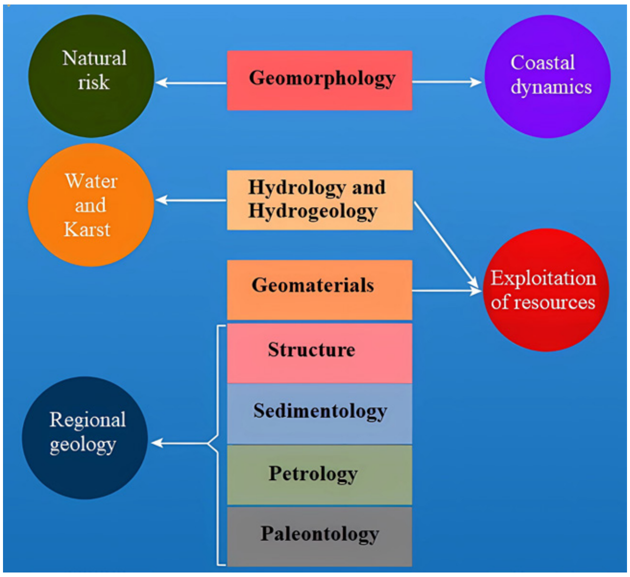

Fig. 4.- The five themes in the study area (Water and karst, Naturel risk, Coastal dynamics, Regional geology, Exploitation of resources) that group the 7 SGI typologies defined by Aoulad-Sidi-Mhend (2019).

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

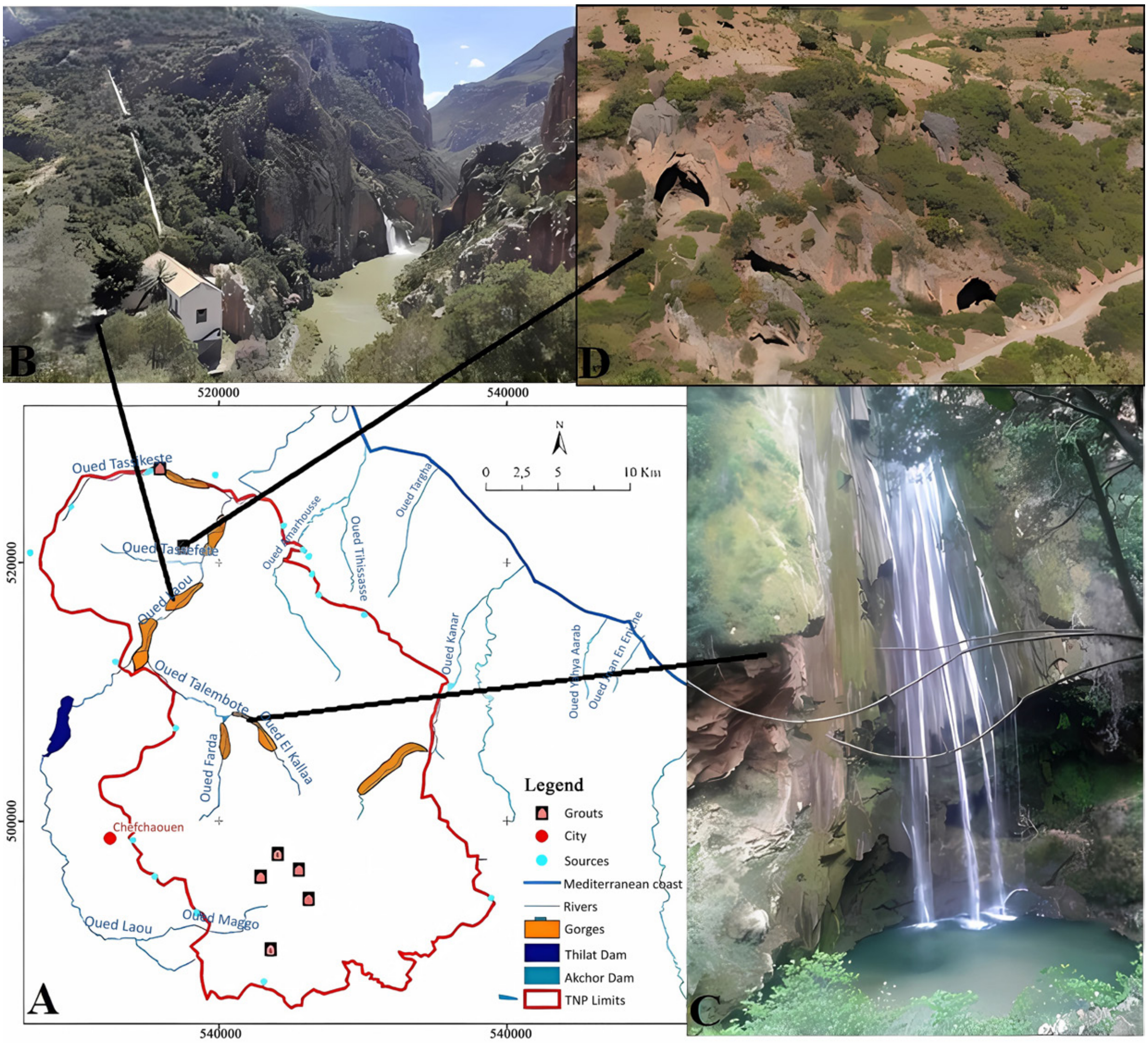

Fig. 5.- A) Map showing localization of structures and manifestations related to the water and karst theme in the area study; B) Throat and spring of Laou river; C) El Kalaa waterfall; D) Hattab cave.

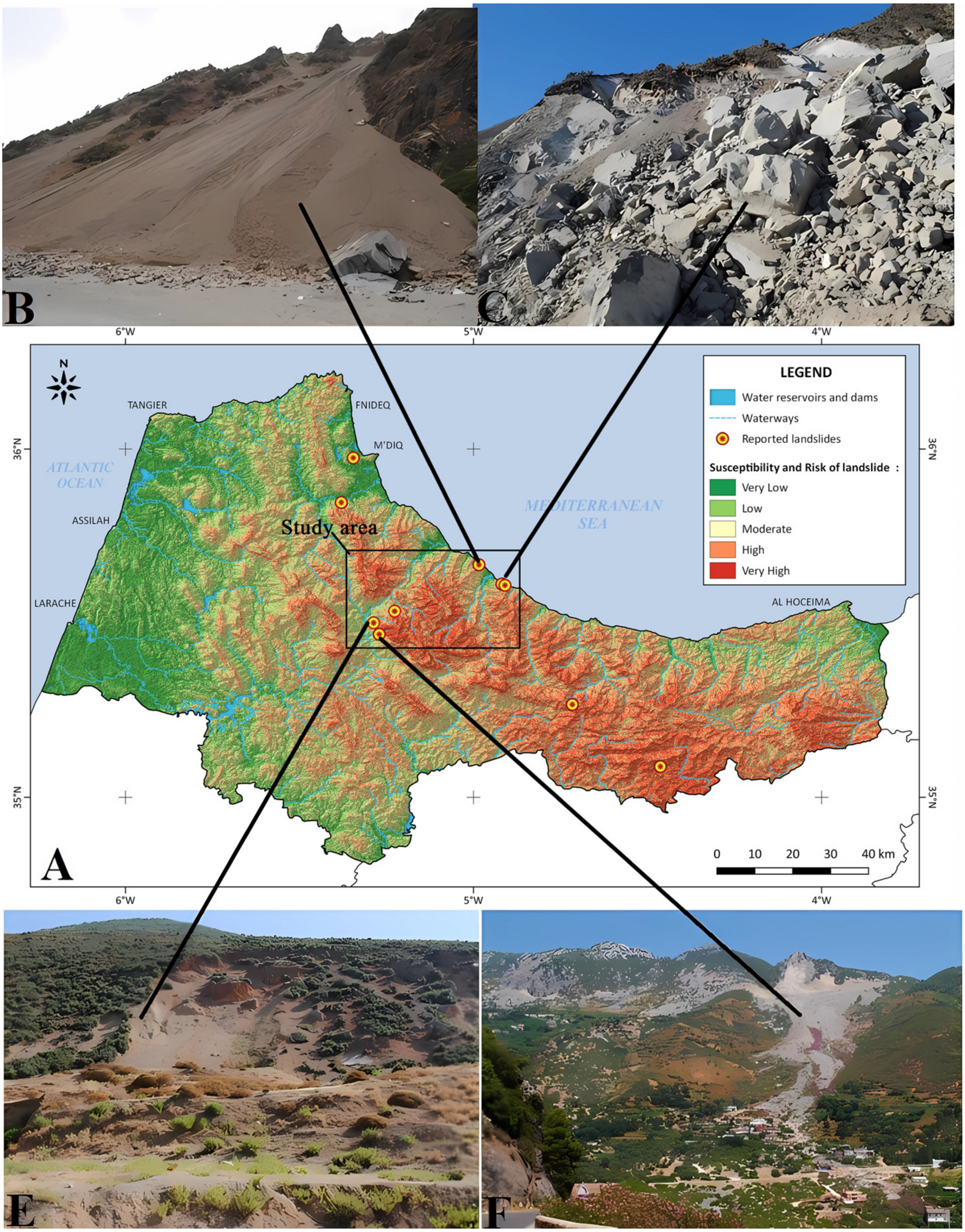

Fig. 6.- Gravitational instability theme in the study area. A) Landslide susceptibility map of the Tangier-Tetouan-Al Hoceima region (N Morocco); B) Azinti landslide; C) Beni Bousera landslide; D) Bouhala landslide; E) Ametrasse rockfall.

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.

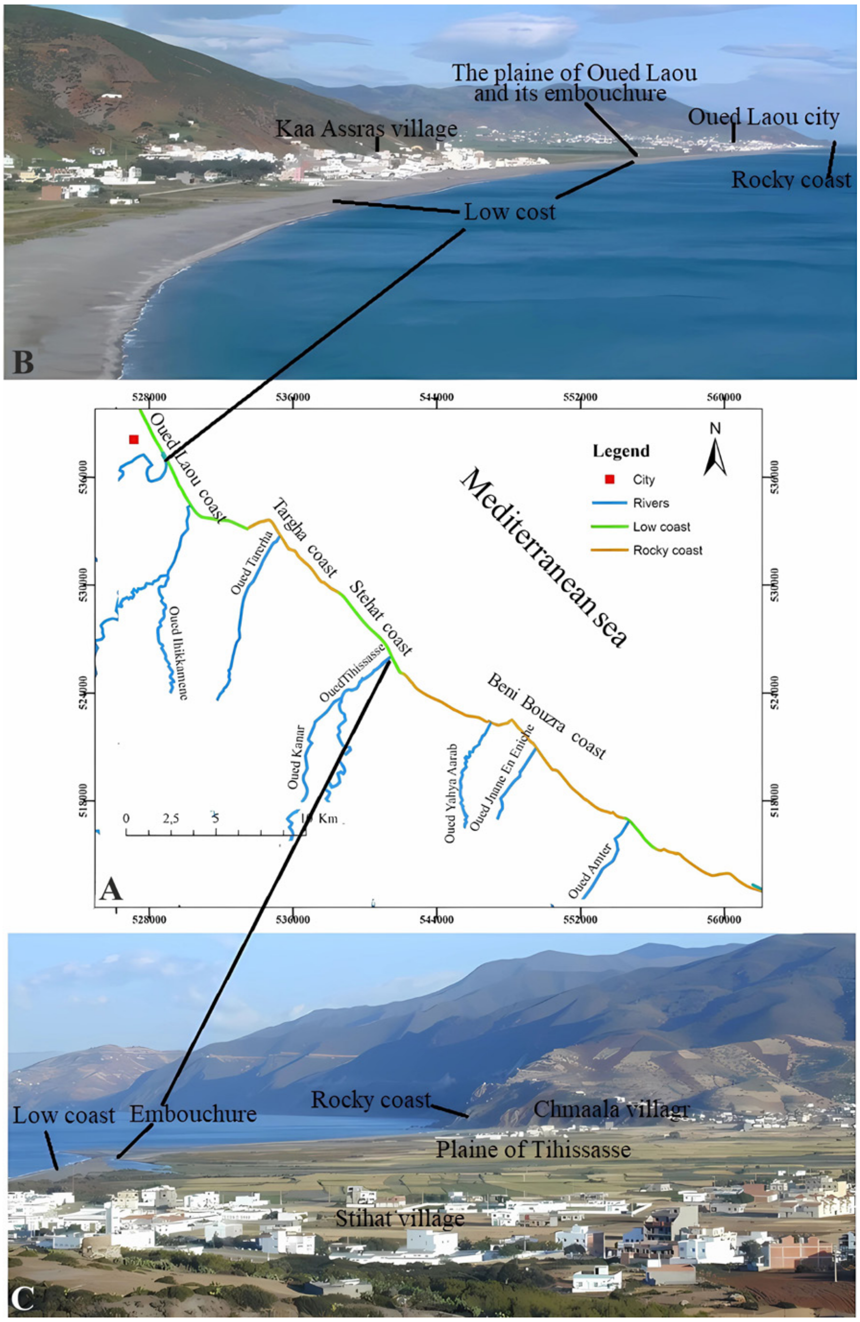

Fig. 7.- Coastal dynamics theme in the study area. A) Map representing the dynamics of the Ghomara coast; B) Panoramic view of the low coast in the Oued Laou area; C) Tighissasse River mouth delta in the low coast, with the rocky coast of Chmaala at the bottom.

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.

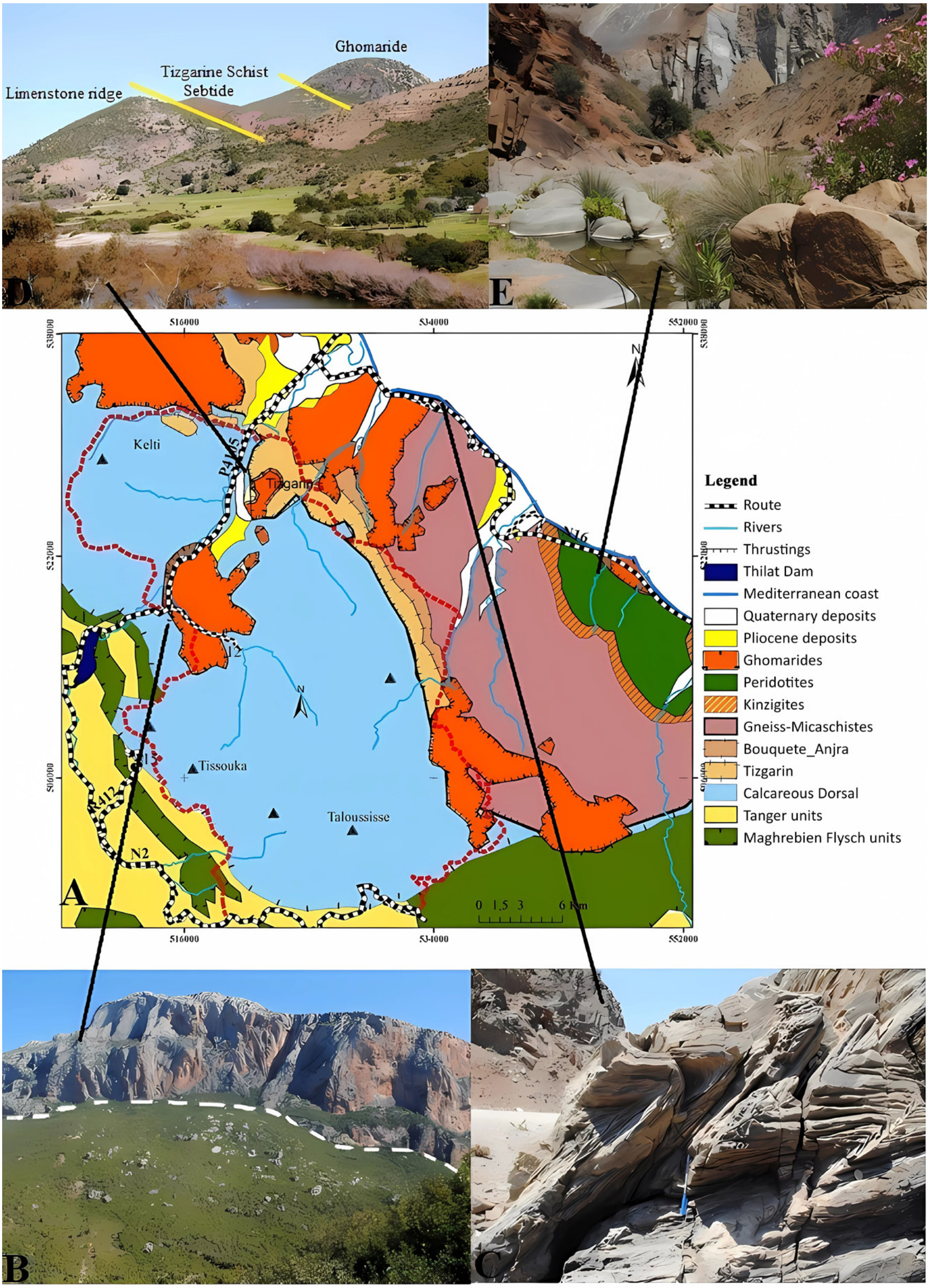

Fig. 8.- A) Regional geology theme in the study area; B) Talembote klippes; C) Micashist-type metamorphic rocks; D) Kodiat Achacha showing the structural relationship between the internal Rif units; E) Peridotites of the Aaraben Valley.

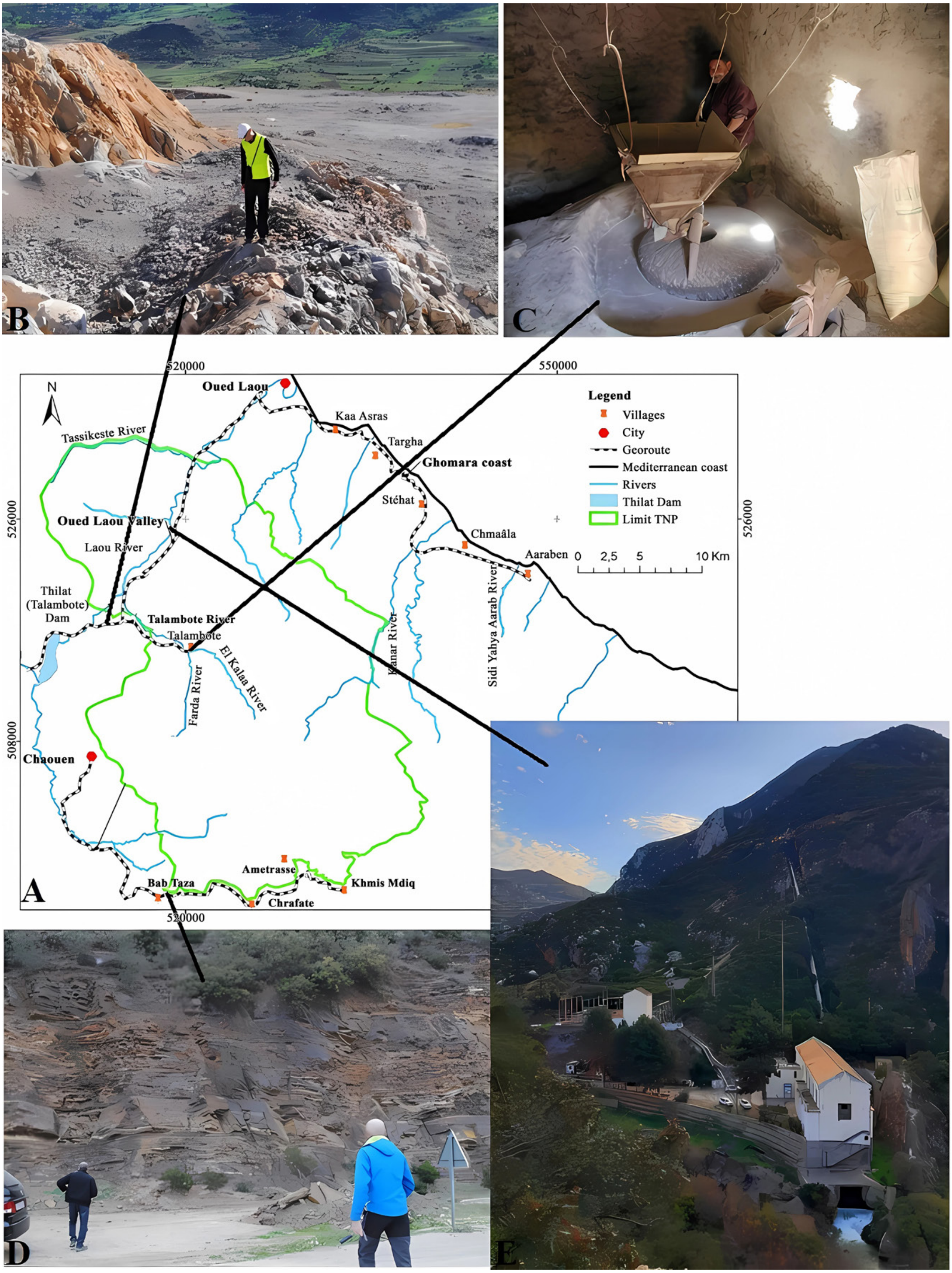

Fig. 9.- Geomaterials and energy theme in the study area. A) Map of study area showing Geomaterials and environment examples. B) Example of exploitation of natural resources in quarry for the extraction of granular material and blocks. C) Water mill of Akchour. D) Phtanites of Bab Taza, a geo-material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

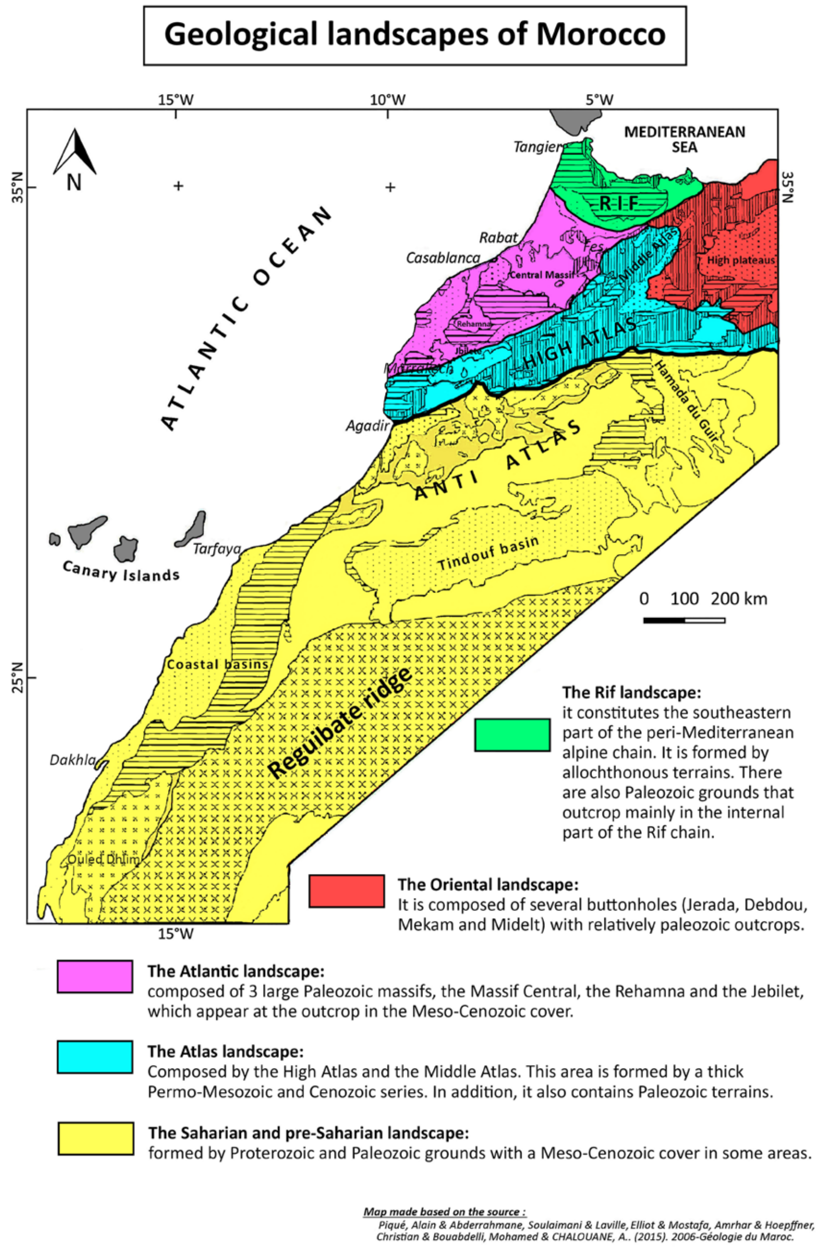

Fig. 10.- Map of landscapes and morphoregions of Morocco (modified from Piqué *et al.*, 1994).

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.

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

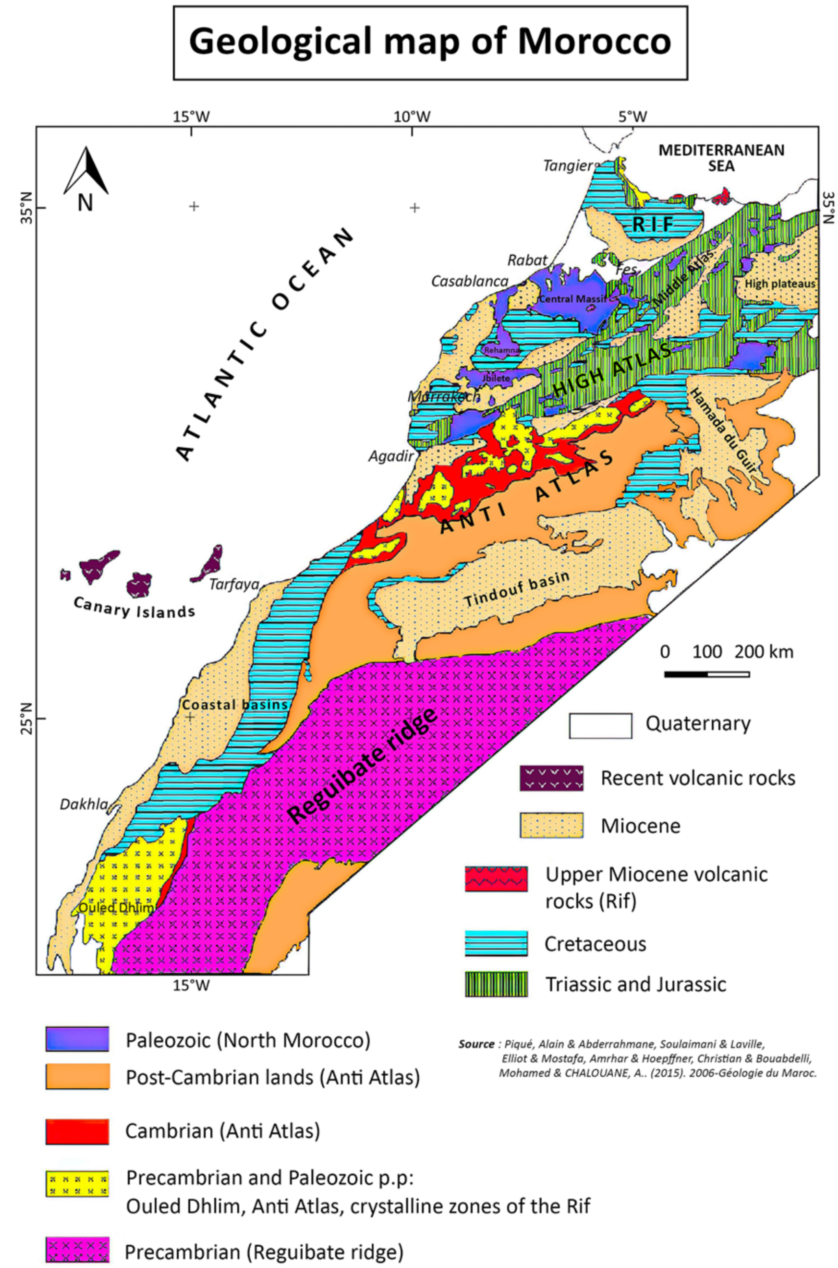

Fig. 11.- Simplified geological map of Morocco (modified from Piqué *et al.*, 1994).

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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References

Alexandrowicz, Z., Kozlowski, S., 1999. From selected geosites to geodiversity conservation-Polish example of modern framework. In: Barettino D, Vallejo M, Gallego E (eds) Towards the balanced management and conservation of the geological heritage in the new millenium. Sociedad Geológica de España, Madrid, Spain, 40-44.

Arrad, T.Y., Errami, E., Ennih, N., 2018., From scientific inventory to socio-economic sustainable development: Tidzi Diapir geosite (Essaouira basin, Morocco). Journal of Chemical, Biological and Physical Sciences, 9. https://doi.org/10.24214/jcbps.D.9.1.00117

Arrad, T.Y., Errami, E., Ennih, N., Ouajhain, B., Ettachfini, E.M., Bouaouda, M.S., 2020. From geoheritage inventory to geoeducation and geotourism implications: Insight from Jbel Amsittene (Essaouira province, Morocco), Journal of African Earth Sciences, 161, 103656. https://doi.org/10.1016/j.jafrearsci.2019.103656

Aoulad-Sidi-Mhend, A., 2014. Implication des autorités locales, de la population et des associations pour la protection du patrimoine géologique et archéologique. Arabian Journal of Earth Sciences 1: 90-93.

Aoulad-Sidi-Mhend, A., 2019. Caractérisation et valorisation du patrimoine géologique du Parc National de Talassemtane et de la côte des Ghomara (Rif septentrional, nord-ouest du Maroc). Doctorat National Université IbnTofail Faculté des Sciences de Kénitra 306 p.

Aoulad-Sidi-Mhend, A. 2020. Patrimoine géologique du Nord-Ouest Maroc. Editions Universitaires Europeennes. ISBN 978-620-2-54080-3/313P.

Aoulad-Sidi-Mhend, A., Maaté, A., Amri, Hlila R., Chakiri S., Maaté S., Martín-Martín M., 2019. The Geological Heritage of the Talassemtane National Park and the Ghomara coast Natural Area (NW of Morocco): Geoheritage. https://doi.org/10.1007/s12371-019-00347-4

Aoulad-Sidi-Mhend, A., Maaté, A., Hlila, R., Martín-Martín, M., Chakiri, S., Maaté, S., 2020. A quantitative approach to geosites assessment of the Talassemtane National Park (NW of Morocco). Estudios Geológicos 76: e123. https://doi.org/10.3989/egeol.43448.520

Aoulad-Sidi-Mhend, A., Cherai, B., Maaté, A. Hlila, R., Amri, I., Chakiri, S., Maaté, S., 2022. Contribution à l'inventaire du patrimoine géologique du Maroc: Les géosites du métamorphisme des Sebtides le long de la côte des Ghomara (Rif interne, NW Maroc). Bulletin de l'Institut Scientifique, Rabat, Section Sciences de la Terre, 44: 71-91, e-ISSN: 2458-7184.

Baadi, K., Sabaoui, A., Tekiout, B., 2020. Methodological Proposal for Assessment Geosites: its Application in Bou-Iblane Region (Middle Atlas, Morocco). Geoheritage 12: 55. https://doi.org/10.1007/s12371-020-00476-1

Beraaouz, M., Macadam, J., Bouchaou, L., Ikenne, M., Ernst, R., Tagma, T., Masrour, M., 2019. An inventory of geoheritage sites in the Draa Valley (Morocco, a contribution to promotion of Geotourism and sustainable development. Geoheritage 11: 241-255. https://doi.org/10.1007/s12371-017-0256-x

Berred, S., 2020. Identification et valorisation du patrimoine géologique du Maroc: cas de la géodiversité et du géotourisme de la région de Tata (Bani geopark, Anti-Atlas). Thèse de Doctorat des Sciences, Université Mohammed V, Rabat, Maroc, 219 p.

Berred, S., Fadli, D., 2016. Géosites et Géomorphosites témoignant de l'instabilité synsédimentaire des séries carbonatées de l'Ediacarien terminal et du Cambrien inférieur (Géoparc du Jbel Bani, Sud Marocain). Notes et Mémoires du service Géologique du Maroc, 15 p.

Berred, S., Fadli, D., Berred, K., 2019a. Aerial interference of Hercynian folds and their morphological peculiarities in the Bani Geopark of southern Morocco. Arabian Journal of Geosciences, 12: 1-10. https://doi.org/10.1007/s12517-019-4537-3

Berred, S., Fadli, D., Di Gregorio, F., Berred, K., 2020. Geological and landscape particularities of Issafen-style chevron pattern in Tata region (Anti-Atlas, South Morocco). Arabian Journal of Geosciences, 13: 689. https://doi.org/10.1007/s12517-020-05713-z

Berred, S., Fadli, D., El Wartiti, M., Zahraoui, M., Berred, K.H., Sadki, R., 2019b. Geomorphosites of the semiarid Tata region: valorization of an unknown geoheritage for geotourism sustainable development (Anti-Atlas, South Morocco). Geoheritage, 11: 1989-2004. https://doi.org/10.1007/s12371-019-00414-w

Berred, K., Youssi, M.E., Berred, S. 2022, Inventorying Rabat-Salé-Kénitra Region's Geological Heritage Within Central Morocco: a Useful Tool for Developing Regional Geotourism Activity. Geoheritage, 14: 91. https://doi.org/10.1007/s12371-022-00723-7

Bollati, I., Smiraglia, C., Pelfini, M., 2013. Assessment and Selection of Geomorphosites and Trails in the Miage Glacier Area (Western Italian Alps). Environmental Management, 51: 951-967. https://doi.org/10.1007/s00267-012-9995-2

Bouari, A., Lazreq, N., Soulaimani, A. Tahiri, A., Aboulfaraj, A., 2021. The Heritage Interest of the Koudiat Ferjane Outcrops of Jebel Ardouz in the M'zoudia Region and Their Protection. Geoheritage, 13: 13. https://doi.org/10.1007/s12371-021-00541-3

Bouzekraoui, H., Barakat, A., Touhami, F., Mouaddine, A., El Youssi, M., 2017. Inventory and assessment of geomorphosite for geotoutism development: case study of ait Bou Oulli valley (central High-Atlas, Morocco). Royal Geographical Society (with the institute of British Geography). https://doi.org/10.1007/s12665-018-7589-x

Bouzekraoui, H., Barakat, A., El Youssi, M., Touhami, F., Mouaddine, A., Hafid, A., Zwoliński, Z., 2018. Mapping geosites as gateways to the geotourism management in Central High-Atlas (Morocco). Quaest iones geographicae, 37: 87-102. https://doi.org/10.2478/quageo-2018-0007

Brilha, J., 2005. Património Geológico e Geoconservação: a Conservação da Natureza na sua Vertente Geológica. Palimage Editores. ISBN: 972-8575-90-4, 183 p.

Brilha, J., 2016. Inventory and Quantitative Assessment of Geosites and Geodiversity Sites: Geoheritage, 8: 119-134. https://doi.org/10.1007/s12371-014-0139-3

Brilha, J., Andrade, C., Azerêdo, A., Barriga, F.J.A.S., Cachão, M., Couto, H., Cunha, P.P., Crispim, J.A., Dantas, P., Duarte, L.V., Freitas, M.C., Granja, M.H., Henriques, M.H., Henriques, P., Lopes, L., Madeira, J., Matos, J.M.X., Noronha, F., Pais, J., Piçarra, J., Ramalho, M.M., Relvas, J.M.R.S., Ribeiro, A., Santos, A, Santos, V., Terrinha, P., 2005. Definition of the Portuguese frameworks with international relevance as an input for the European geological heritage characterisation. Episodes 28: 177-186. https://doi.org/10.18814/epiiugs/2005/v28i3/004

Brilha, J., Alcala, L., Almeida, A., Araújo, A., Azerêdo, A., Azevedo, M.R., Barriga, F., Brum da Silveira, A., Cabral, J., Cachão, M., Caetano, P., Cobos, A., Coke, C., Couto, H., Crispim, J., Cunha, P.P., Dias, R., Duarte, LV., Dória, A., Falé, P., Ferreira, N., Ferreira, Soares, A., Fonseca, P., Galopim, de Carvalho, A., Gonçalves, R., Granja, H., Henriques, M.H., Kullberg, J.C., Kullberg, M.C., Legoinha, P., Lima, A., Lima, E., Lopes, L., Madeira, J., Marques, J.F., Martins, A., Martins, R., Matos, J., Medina, J., Miranda, R., Monteiro, C., Moreira, M., Moura, D., Neto de Carvalho, C., Noronha, F., Nunes, J.C., Oliveira, J.T., Pais, J., Pena dos Reis, R., Pereira, D., Pereira, P., Pereira, Z., Piçarra, J., Pimentel, N., Pinto de Jesus, A., Prada, S., Prego, A., Ramalho, L., Ramalho, M., Ramalho, R., Relvas, J., Ribeiro, A., Ribeiro, MA., Rocha, R., Sá, A., Santos, V., Sant'ovaia, H., Sequeira, A., Sousa, M., Terrinha, P., Valle Aguado, B., Vaz N., 2010. Inventário nacional do património geológico: abordagem metodológica e resultados. e-Terra, 18 (1).

Bruschi, V.M., Cendrero, A., 2009. Direct and parametric methods for the assessment of geosites and geomorphosites. In: Reynard, E., Coratza, P., Regolini-Bissig G (eds) Geomorphosites. Verlag Dr. Friedrich Pfeil, München. Section II, 73-88.

Bruschi, V.M., Cendrero, A., Albertos, J.A.C., 2011. A statistical approach to the validation and optimisation of geoheritage assessment procedures. Geoheritage, 3: 131-149. https://doi.org/10.1007/s12371-011-0038-9

Carcavilla, L., López Martínez, J., Durán Valsero, J.J., 2007. Patrimonio geológico y geodiversidad: investigación, conservación, gestión y relación con los espacios naturales protegidos. Cuadernos del Museo Geominero, 7, IGME, Madrid.

Carcavilla, L., Durán, J.J., Garcia-Cortés, A., López-Martinez, J., 2009. Geological heritage and geoconservation in Spain: past, present, and future. Geoheritage, 1: 75-91. https://doi.org/10.1007/s12371-009-0006-9

Cendrero, A., 1996a. El patrimonio geológico. Ideas para su protección, conservación y utilización. In: El patrimonio geológico. Bases para su valoración, protección, conservación y utilización. Serie Monografías del Ministerio de Obras Públicas, Transportes y Medio Ambiente. Ministerio de Obras Públicas, Transportes y Medio Ambiente, Madrid, 17-27.

Cendrero, A., 1996b. Propuestas sobre criterios para la clasificación y catalogación del patrimonio geológico. In: El patrimonio geológico. Bases para su valoración, protección, conservación y utilización. Serie Monografías del Ministerio de Obras Públicas, Transportes y Medio Ambiente. Ministerio de Obras Públicas, Transportes y Medio Ambiente, Madrid, 29-38.

Coratza, P., Giusti, C., 2005. Methodological proposal for the assessment of scientific quality of geomorphosites. Il Quaternario, Italien. Journal of Quaternary Science, 18: 307-313.

De Lima, F.F., Brilha, J.B., Salamuni, E., 2010. Inventorying geological heritage in large territories: a methodological proposal applied to Brazil. Geoheritage, 2: 91-99. https://doi.org/10.1007/s12371-010-0014-9

De Wever, P., Le Nechet, Y., Cornée, A., 2006. Vade-mecum pour l'inventaire du patrimoine géologique national. Mémoire hors service Société géologique de France. 12: 162. https://doi.org/10.4000/ocim.267

De Wever, P., Egoroff, G., Cornée, A., Lalanne, A. 2014. Géopatrimoine en France. Mémoire Hors-Séries de la Société géologique de France, 14: 180.

Díaz-Martínez, E., Díez-Herrero, A., 2011. Los elementos biológicos y culturales de interés geológico: un patrimonio a conservar. In Fernández-Martínez E, Castaño de Luis R (eds) Avances y retos en la conservación del Patrimonio Geológico en España. Actas de la IX Reunión Nacional de la Comisión de Patrimonio Geológico (Sociedad Geológica de España), Universidad de León, 85-90.

Durán Valsero, J.J., Urquí, L., López-Martínez, J., 2005. Patrimonio geológico: una panorámica de los últimos 30 años en España. Boletín de la Real Sociedad Española de Historia Natural (Sec. Geol.), 100: 277-287.

Eder, W., Patzak, M., 2004. Geoparks-geological attractions: a tool for public education, recreation and sustainable economic development. Episodes, 27: 162-164. https://doi.org/10.18814/epiiugs/2004/v27i3/001

El Hadi, H., Tahiri, A., Simancas, J.F., González-Lodeiro, F., Azor, A., Martínez-Poyatos, D., 2011. Geoheritage in Morocco: the Neoproterozoic Ophiolite of Bou Azzer Central Anti-Atlas. Geoheritage, 3: 89-96. https://doi.org/10.1007/s12371-011-0032-2

El Hadi, H., Tahiri, A., Simancas, J.F., González-Lodeiro, F., Azor, A., Martínez-Poyatos, D., El Maidani, A., 2012. The Precambrian ophiolites of Bou Azzer Anti Atlas: an example of geoheritage in Morocco. Geo-Temas, 13.

El Hadi, H., Tahiri, A., Simancas, F., Lodeiro, F.G., Azor, A., Martínez Poyatos, D.J., 2014. Pillow lavas of Rabat northwestern Moroccan Meseta: transitional geochemical signature of magmas set up in an early Ordovician extending platform. European Journal of Scientific Research, 122: 45-57.

El Hadi, H., Tahiri, A., Brilha, J., El Maidani, A., Baghdad, B., Zaidi, A., 2015. Geodiversity examples of Morocco: from inventory to regional geotourism development. Open Journal of Ecology, 5: 409-419. https://doi.org/10.4236/oje.2015.59034

El Hassani, A., Aboussalam, S., Becker, T., El Wartiti, M., El Hassani, F., 2017. Patrimoine géologique marocain et développement durable: l'exemple du Dévonien du Tafilalt, Anti-Atlas oriental. Geologues, Société Géologique de France, 194: 112-117.

El Wartiti, M., Malaki, A., Zahraoui, M., DI Gregorio, F., De Waele, J., 2009. Geosites and touristic development of the northwestern Tabular Middle Atlas of Morocco. In: Marini, A., Talbi, M. (eds) Desertification and Risk Analysis Using High and Medium Resolution Satellite Data. NATO Science for Peace and Security Series C: Environmental Security. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-8937-4_13

El Wartiti, M., Zahraoui, M., El Hassani, A., 2017. Les marqueurs permiens comme patrimoine géologique à promouvoir et à protéger dans le massif hercynien du Maroc central. Geologues, Société Géologique de France 194: 118-126.

Ennіouar, A., Lagnaoui, A., Habib, A., 2013. A Middle Jurassic sauropodtracksite in the Argana Basin, Western High Atlas, Morocco: an example of paleonichnological heritage for sustainable geotourism. https://doi.org/10.1016/j.pgeola.2013.09.003

Proceedings of the Geologists' Association, 125: 114-119. https://doi.org/10.1016/j.pgeola. 2013.09.003

Enniouar, A., Errami, E., Lagnaoui, L., Boualla, O., 2015. Geoheritage of Doukkala-Abda region (Morocco): a tool for local socioeconomical sustainable development. In Geoheritage to Geoparks: Case Studies from Africa and Beyond, Springer Verlag ISBN 978-3- 319-10707-3. https://doi.org/10.1007/978-3-319-10708-0_7

Errami, E., Ennih, E., Brocx, M., Semeniuk, V., Otmane, K., 2013. Geoheritage, Geoconservation and aspiring Geoparks in Morocco: the Zenaga inlier. Rendiconti Online Società Geologica Italiana, 28: 49-53. Roma ISSN 2035-8008.

Errami, E., Brocx, M., Semeniuk, V., (Eds). 2015a. From Geoheritage to Geoparks: case studies from Africa and beyond. Springer Verlag, 269 p. ISBN 978-3-319-10707-3. https://doi.org/10.1007/978-3-319-10708-0

Errami, E., Brocx, M., Semeniuk, V., Ennih, N., 2015b. Geosites,

sites of special scientific interest, and potential geoparks in the Anti-Atlas (Morocco). In Errami, E., Brocx, M., Semeniuk, V., (Eds): From Geoheritage to Geoparks: case studies from Africa and beyond. Springer, Verlag ISBN 978-3-319-10707-3. https://doi.org/10.1007/978-3-319-10708-0

Fadli, D., 2014. Les "coeurs" de Tata et leurs dérivés: géomorphosites emblématiques pour un géotourisme incontounable du Sud marocain, 1st edn. Faculté des Sciences de Rabat, RABAT, 270 p.

Fidan, B., 2017. Université Mohammed V de Rabat, l'Institut Scientifique, Rabat Série Géologie et Géographie physique, n° 24, Notes & Mémoire. N°556 au N°564, 61 p.

Fassoulas, C., Mouriki, D., Dimitriou-Nikolakis, P., Iliopoulos, G., 2012. Quantitative assessment of geotopes as an effective tool for geoheritage management. Geoheritage, 4: 177-193. https://doi.org/10.1007/s12371-011-0046-9

Frey, M. L., Schmitz, P., Weber, J., 2021. Messel Pit UNESCO World Heritage Fossil Site in the UNESCO Global Geopark Bergstrasse-Odenwald, Germany-Challenges of Geoscience Popularisation in a Complex Geoheritage Context. Geoconservation Research, 4(2): 524-546.

Fuertes-Gutiérrez, I., Fernández-Martínez, E., 2010. Geosites inventory in the Leon Province (Northwestern Spain): a tool to introduce geoheritage into regional environmental management. Geoheritage 2(1-2): 57-75. https://doi.org/10.1007/s12371-010-0012-y

García-Cortés, A., Carcavilla Urquí, L., 2009. Documento metodológico para la elaboración del inventario español de lugares de interés geológico (IELIG), version 12. Instituto Geológico y Minero de España, Madrid, 64 p.

Grandgirard, V., 1999. Inventaire des géotopes d'importance nationale. Geologia Insubrica, 4: 25-53.

Gray, J.M., 2013. Geodiversity: valuing and conserving abiotic nature, 2nd édition. John Wiley & Sons, Chichester.

Hintermann, B., Weber, S.A., 2001. La nature demain. Rapport de l'étude pour un projet d'inventaire et de protection des géotopes vaudois. Ecologie et géographie appliquées, Rue de l'Eglise-Catholique 8 1820 Montreux, 2: 1-50.

JNCC., 1977. Guidelines for selection of Earth Science SSSIs.

Khoukhouchi, M., Errami, E., Hassou, N., Irzan, E., 2018. The geomorphological heritage of the Oualidia and Sidi Moussa lagoons: assessment and promotion for a sustainable human and socio-economic development. Journal of Scientific Research and Studies, 5: 73-87.

Khouraiss, K., El Hariri, K., El Albani, A., Azizi, A., Mazurier, A., Lefebvre, B., 2019. Digitization of fossils from the Fezouata Biota (Lower ordovician, Morocco): evaluating computed tomography and photogrammetry in collection enhancement. Geoheritage, 11: 1889-1901. https://doi.org/10.1007/s12371-019-00403-z

Lahmidi, S., Lagnaoui, A., Bahaj, T., El Adnani, A., Fadli, D., 2020. First inventory and assessment of the Geoheritage of Zagora province from the project Bani Geopark (South-Eastern Morocco), Proceedings of the Geologists' Association, 131: 511-527. https://doi.org/10.1016/j.pgeola.2020.05.002

Lapo, A.V., Davydov, V.I., & Pashkevich, N.G., Petrov, V.V., Vdovets, M.S., 1993. Methodic principles of study of geological monuments of nature in Russia. Stratigraphy and Geological Correlations I(6): 636-644.

McKeever, P., Zouros, N., Patzak, M., Weber, J., 2010. The UNESCO global network of national geoparks. In: Newsome D, Dowling R (eds) Geotourism: the tourism of geology and landscape. Goodfellow Publishers Ltd, Oxford, 221-230. https://doi.org/10.23912/978-1-906884-09-3-1071

Malaki, A., 2006. Geosites: Interet Scientifique, Patrimoine Culturel et VisEes Socio-Economiques, au Niveau d'Ifrane, Azrou, AînLeuh et el Hajeb (Causse Moyen Atlasique). Thèse de Doctorat, Faculté des Sciences de Rabat, Maroc.

Martín-Martín, M., Sanz de Galdeano, C., Moliner-Aznar, S., 2021. "The Geological Heritage of Salobreña (South Spain): example of a touristic area". American Research Journal of Humanities and Social sciences, 2: 1-17. https://doi.org/10.21694/2642-3022.21001

M'Barki, L., 2017. Etude géomorphologique des géosystèmes oasiens et montagneux de l'Anti-Atlas occidental marocain. Implications géodidactiques et géotouristiques. Thèse de doctorat en Géosciences et Géoenvironnement. Faculté des Sciences, Agadir, Université Ibn Zohr, 220 p.

Mehdioui, S., El Hadi, H., Tahiri, A., Brilha, J.B., El Haibi, H., Tahiri, M., 2020. Inventory and Quantitative Assessment of Geosites in Rabat-Tiflet Region (North Western Morocco): Preliminary Study to Evaluate the Potential of the Area to Become a Geopark. Geoheritage, 12: 35. https://doi.org/10.1007/s12371-020-00456-5

Metaseria, D., Asfawossen, A., Mogessie, A., 2004. Contribution of geology to the growth of the tourism industry in Ethiopia. 20th Colloquium African Geology, Abstr. Vol., 131.

Michard, A., 1976. Eléments de géologie Marocaine. Notes et mémoires du Service Géologique du Maroc, Rabat, 252 p.

Michard, A., Saddiqi, O., Chalouan, A., Eh-Cherki Rjimati, E., Mouttaqi A., 2011. Présentation des circuits. Introduction à la géologie du Maroc. Volume 1. Notes et Mémoires du Service Géologique du Maroc. N°556. 73 p.

Mirari, S., Aoulad-Sidi-Mhend, A., Benmlih, A., 2020. Geosites for Geotourism, Geoheritage, and Geoconservation of the Khnefiss National Park, Southern Morocco. Sustainability, 12: 7109. https://doi.org/10.3390/su12177109

Moliner-Aznar, S., Martín-Martín, M., Rodríguez-Estrella, T., Romero-Sánchez, G., García-Lara, A., 2021. Geogical Sites in Sierra Espuna-Mula depression area (Murcia province, SE Spain). Revista de la Sociedad Geológica de España, 34: 43-56. https://doi.org/10.3390/geosciences11010034

Moliner-Aznar, S., 2022. Caracterización y valorización del patrimonio geológico del área de Sierra Espuña (Cordillera Bética: SE, España). PhD Thesis, Univ. Alicante. 310 p. https://rua.ua.es/dspace/handle/10045/124010

Nahraoui, F., El Wartiti, M., Zahraoui, M., Dabi, S., 2011. Geomorphosite Valorization a View to Sustainable Development: Case of Ait Hajji, Oued Boulahmayel Valley, Central Morocco. Journal of Geographic Information System, 3: 12-17. https://doi.org/10.4236/jgis.2011.31002

Nahraoui, F., 2016. Le patrimoine géologique du Massif Central marocain: atouts pour un géotourismeintégré. Thèse de doctorat « Sciences de la Terre ». Faculté des sciences-Rabat, Maroc.

Noubhani, A., 2015. Late cretaceous and lower Paleogene Moroccan phosphates: geotourism opportunities. In Errami, E., Brocx, M., Semeniuk, V. (Eds), From Geoheritage to Geoparks: Case Studies from Africa and Beyond. Springer Verlag. 125-133. https://doi.org/10.1007/978-3-319-10708-0_8

Oukassou, M., Boumir, Kh, B.K., Benshili, Kh., Ouarhache, D., Lagnaoui, A., Charrière, A., 2019. The Tichoukt massif, a geotouristic play in the folded Middle Atlas Morocco. Geoheritage, 11: 371-379. https://doi.org/10.1007/s12371-018-0287-y

Parkes, M.A., Morris, J.H., 1999. The Irish Geological Heritage Programme. In: Barettino D, Vallejo, M., Gallego, E., (eds) Towards the balanced management and conservation of the geological heritage in the new millenium. Spain, Sociedad Geológica de España, Madrid, 60-64.

Pralong, J.P., 2006. Géotourisme et utilisation des sites naturels d'intérêt pour les sciences de la Terre: les régions de Crans-Montana-Sierre (Valais, Alpes suisses) et Chamonix-Mont-Blanc (Haute-Savoie, Alpes françaises). Thèse de doctorat, Lausanne, Institut de géographie, Travaux et recherches n° 32. 268 p.

Pralong, J.P., Reynard, E., 2005. A proposal for the classification of geomorphological sites depending on their tourist value. Quaternario, 18: 315-321.

Pereira, P., Pereira, D.I., Alves M.I.C., 2007. Geomorphosite assessment in Montesinho Natural Park (Portugal). Geographica Helvetica, 62: 159-168. https://doi.org/10.5194/gh-62-159-2007

Pereira, P., Pereira, D.I., 2010. Methodological guidelines for geomorphosite assessment. Géomorphologie, Relief, Processus, Environnement, 2: 215-222. https://doi.org/10.4000/geomorphologie.7942

Pereira, P., Pereira, D.I., 2012. Assessment of geosites tourism value in geoparks: the example of Arouca Geopark (Portugal). Proceedings of the 11th European Geoparks Conference, Arouca: 231-232.

Piqué, A., 1994. Géologie du Maroc. Les domaines régionaux et leur évolution structurale. Édition Pumag. Marrakech, 284 p.

Piqué, A., Michard, A., 1989. Moroccan Hercynides: a synopsis. The Paleozoic sedimentary and tectonic evolution at the northern margin of West Africa. American Journal of Science, 289: 286-330. https://doi.org/10.2475/ajs.289.3.286

Piqué, A., Soulaimani, A., Amrhar, M., Laville, E., Bouabdelli, M., Hoepffner, C., Chalouan, A., 2006. Géologie du Maroc: les domaines régionaux et leur évolution structural, 271 p.

Reynard, E., Berger, J.P., Felber, M., Heitzmann, P., Hipp, R., Hug, W., Imper, D., Jordan P., Schenker, J., Von Salis, K., 2004. Geoparks in Switzerland, 32nd Int. Geological Congress, Firenze, Abstracts volume. Management of Geomorphological Heritage at the Regional Scale. Geoheritage, 8: 43-60. https://doi.org/10.1007/s12371-015-0153-0

Reynard, E., Fontana, G., Kozlik, L., Scapozza, C., 2007. A method for assessing scientific and additional values of geomorphosites. Geographica Helvetica. Geogr Helv 62(3):148-158. https://doi.org/10.5194/gh-62-148-2007

Reynard, E., Laigre, L., Kramar, N., (Eds) 2011. Les géosciences au service de la société. Actes du colloque en l'honneur du Professeur Michel Marthaler, 24-26 juin 2010, Lausanne (Géovisions n° 37). Institut de géographie, Université de Lausanne.

Reynard, E., 2012. Geoheritage protection and promotion in Switzerland. European Geologist 34: 44-47.

Reynard, E., Perret, A., Grangier, L., Kozlik, L., 2012. Methodological approach for the assessment, protection, promotion and management of geoheritage. Geophys Res Abstr 14: EGU2012-3740.

Reynard, E., Coratza, P., 2013. Scientific research on geomorphosites. A review of the activities of the IAG working group on geomorphosites over the last twelve years. Geogr Fis Dinam Quat 36: 159-168.

Reynard, E., Perret, A., Bussard, J., Grangier, L., Martin, S., 2016. Integrated Approach for the Inventory and Management of Geomorphological Heritage at the Regional Scale. Geoheritage 8: 43-60. https://doi.org/10.1007/s12371-015-0153-0

Saddiqi, O., Rjimati, E., Michard, A., Soulaimani, A., Ouanaimi, H., 2015. Recommended geoheritage trails in southern Morocco: a 3 Ga record between the Sahara Desert and the Atlantic Ocean. In Errami, E., Brocx, M., Semeniuk, V. (Eds), From Geoheritage to geoparks: case studies from Africa and beyond. Springer Verlag ISBN 978-3-319-10707-3. https://doi.org/10.1007/978-3-319-10708-0_6

Schlüter, T., Kibunja, M., Kohring, R. 2001. Geological Heritage in East Africa. Its Protection and Conservation. Documenta Naturae, 136: 39-49.

Schlüter, T., 2008. Women and the International Year of Planet Earth. Proceedings of the Fourth International Conference of the Association of African Women Geoscientists (AAWG), Cairo, 14-16 April 2008, 14-15. https://doi.org/10.1130/1052-5173(2008)18[14:IYOPE]2.0.CO;2

Somma, R., 2022. The Inventory and Quantitative Assessment of Geodiversity as Strategic Tools for Promoting Sustainable Geoconservation and Geo-Education in the Peloritani Mountains (Italy). Education Sciences, 12(9), 580. https://doi.org/10.3390/educsci12090580

Tahiri, A., El Hassani, A., El Hadi, H., 2010. Le patrimoine géologique du Maroc: l'exemple de la géodiversité paléozoïque de la région de Rabat Salé Zemmours Zaers. Géologie de la France, 1: 79-88.

Viljoen, M.J., Reimold, W.U., 1999. An Introduction to South Africa's Geological and Mining Heritage. Mintek, Randburg, 193 p.

Wimbledon, W.A., Benton, M.J., Bevins, R.E., Black, G.P., Bridgland, D.R., Cleal, C.J., Cooper, R.G., May, V.J., 1995. The development of a methodology for the selection of British Geological sites for geoconservation: part 1. Modern Geology, 20: 159-202.

Wimbledon, W.A. 2011., Geosites: A mechanism for protection, integrating national and international valuation of heritage sites. Geologia dell'Ambiente, supplemento n. 2/2011:13-25.

Wimbledon, W.A., Smith-Meyer, S., 2012. Geoheritage in Europe and its conservation. ProGEO, Oslo.

Zouros, N., 2004. The European Geoparks Network. Geological heritage protection and local development. Episodes, 27: 165-171. https://doi.org/10.18814/epiiugs/2004/v27i3/002

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PATRIMONIO GEOLÓGICO DE LA RESERVA NATURAL COMUNITARIA DE DINDEFELO (SENEGAL): INVESTIGACIÓN GEOLÓGICA PARA UN DESARROLLO SOCIOECONÓMICO SOSTENIBLE

Geoheritage of the Dindefelo Community Nature Reserve (Senegal): Geological research for sustainable socioeconomic development

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Abstract: *Within ecotourism, geotourism is currently a less developed but increasingly demanded sector. Geoheritage takes more weight in the enhancement of protected natural areas, such as the Dindefelo Nature Reserve (Senegal). This reserve has a geological history that spans more than 2,300 My linked to the evolution of the West African Craton and the opening of the Madina Kouta basin. This work aims to assess the geological heritage of the reserve. The final objective is to promote economic growth in the area through the development of geotourism. To do so, a sedimentological and petrological field investigation has been conducted. With the information obtained, tourist sites have been considered from a geological perspective and developed for public outreach. As a result, a petrological and sedimentological characterization of geological formations of the reserve has been accomplished. This work describes the geology of the reserve, which is mainly composed of the sedimentary filling of the Meso- and Neoproterozoic Madina Kouta basin over a Paleoproterozoic metamorphic and igneous substratum. The nature of the sedimentary formations varies from tidal flats to the record of a global glacial period. There is also evidence for subvolcanic activity and horizons of alterites developed on the sedimentary units. From these data, 4 geo-zones and 5 geosites are proposed as geoheritage representative of the reserve, but geosite inventories must be further developed with future investigations.*

Keywords: *ecotourism, Dindefelo, geoheritage, Proterozoic, Senegal.*

Resumen: *El geoturismo es un sector actualmente poco desarrollado, pero cada vez más demandado. El patrimonio geológico toma cada vez más peso en la puesta en valor de los espacios naturales protegidos. La Reserva Natural Comunitaria de Dindefelo presenta una historia geológica que abarca más de 2.300 Ma, ligada a la evolución del Cratón de África Occidental y la apertura de la cuenca de Madina Kouta. Este trabajo pretende valorizar el patrimonio geológico de la reserva de Dindefelo para fomentar el crecimiento económico en la zona a través del desarrollo del geoturismo. Con este fin, se ha llevado a cabo una* *investigación petrológica y sedimentológica sobre el terreno. Con esta información se han valorizado desde una perspectiva geológica algunos sitios turísticos previamente existentes y, con el desarrollo de este conocimiento, se ha realizado un proceso de divulgación. Como resultado, se ha obtenido la caracterización geológica de la reserva. Este trabajo describe la geología de la reserva, que está principalmente compuesta por los depósitos sedimentarios de relleno de la cuenca meso y neoproterozoica de Madina Kouta sobre un sustrato metamórfico e ígneo paleoproterozoico. La naturaleza de las formaciones sedimentarias varía entre llanuras de marea y el registro de un período glacial global. También hay evidencias de actividad subvolcánica y unos horizontes de alteritas desarrollados sobre las formaciones sedimentarias. A partir de estos datos se sugieren 4 geozonas y 5 lugares de interés geológico como parte del inventario del patrimonio geológico representativo de la reserva, aunque se deben desarrollar con futuras investigaciones.*

Palabras clave: *ecoturismo, Dindefelo, patrimonio geológico, Proterozoico, Senegal.*

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Introducción

En el artículo 38 de la Ley 42/2007 de Patrimonio Natural y de la Biodiversidad de España se define el “Patrimonio Geológico” como el conjunto de recursos naturales geológicos de valor científico, cultural y/o educativo, ya sean formaciones y estructuras geológicas, formas del terreno, minerales, rocas, meteoritos, fósiles, suelos y otras manifestaciones geológicas que permiten conocer, estudiar e interpretar a) el origen y evolución de la Tierra, b) los procesos que la han modelado, c) los climas y paisajes del pasado y presente, y d) el origen y evolución de la vida. Este concepto permite relacionar los elementos abióticos con otros aspectos del territorio, como el clima, la economía o la cultura (Palacio Prieto *et al*., 2018). Los requisitos de la Organización de las Naciones Unidas para la Educación, la Ciencia y la Cultura (UNESCO) para otorgar la categoría de geoparque mundial establecen que la zona, además de poseer un patrimonio geológico de relevancia internacional, debe vincularlo al resto del patrimonio natural, cultural u otros aspectos intangibles de la zona, y el conjunto de ellos debe ser de alto valor (https://www.geoparquebiobio.cl/wp-content/uploads/sites/87/2019/03/Geoparques-Mundiales-de-la-UNESCO.pdf).

El patrimonio geológico de un lugar está formado por el conjunto de puntos interesantes desde un punto de vista geológico y divulgativo, denominados en España Lugares de Interés Geológicos (LIG) (https://www.igme.es/patrimonio/PG/patrimonioG.htm). Estos deben ser preservados como parte importante del patrimonio natural (Wimbledon, 2012; Carcavilla *et al*., 2013).

El patrimonio geológico es un potencial turístico cada vez más reclamado dentro del ámbito del turismo ambiental o ecoturismo (Hose *et al*., 2011). Esta nueva modalidad, denominada geoturismo, es entendida como la explotación de los atractivos estéticos, que se incrementan con el conocimiento geológico y geomorfológico del paisaje. Aunque hay quien es estricto en la aplicación de este concepto, la UNESCO recomienda incorporar una visión más multidisciplinar, más abierta a los diferentes valores naturales y culturales del territorio donde la geología se presenta como elemento estructural (Hilario *et al*., 2017).

Las expresiones más claras de la explotación del geoturismo son la Red Global de Geoparques (GGN, *Global Geoparks Network*) y la Red Europea de Geoparques (EGN, *European Geoparks Network*) (Dóniz-Páez *et al*., 2020). En ellas se observa que la existencia de un geoparque reduce el desempleo y la emigración de las zonas rurales, fomentando el desarrollo local (Farsani *et al*., 2010). En contraste, aunque la Red Africana de Geoparques (AUGGN, *African UNESCO Global Geoparks Network*) está creada, se encuentra aún por desarrollar, existiendo en África sólo dos geoparques, en Tanzania y en Marruecos.

En el caso de la Reserva Natural Comunitaria de Dindefelo (RNCD), la presencia de especies emblemáticas como el chimpancé de África del oeste (*Pan troglodytes verus*), en peligro crítico de extinción según la Unión Internacional para la Conservación de la Naturaleza (UICN) (2020), la integración del paisaje Peul en el país Bassari (Patrimonio Mundial de la UNESCO en la categoría de Paisaje Cultural) y las cascadas que caracterizan la zona desde el punto de vista paisajístico, son el conjunto de atractivos que han llamado la atención de los turistas cada año. Ahora se propone a la geología como parte esencial del valor de la reserva.

Marco geográfico

La RNCD se localiza en la región de Kédougou, al sureste de Senegal, concretamente, en el distrito de Bandafassi del Departamento de Kédougou. Está limitada al sur y suroeste por la frontera de Guinea Conakry, y al este por el río Gambia (Fig. 1). Se extiende al sur del Parque Nacional Niokolo Koba y al norte de las montañas guineanas de la cordillera Fouta-Djalon.

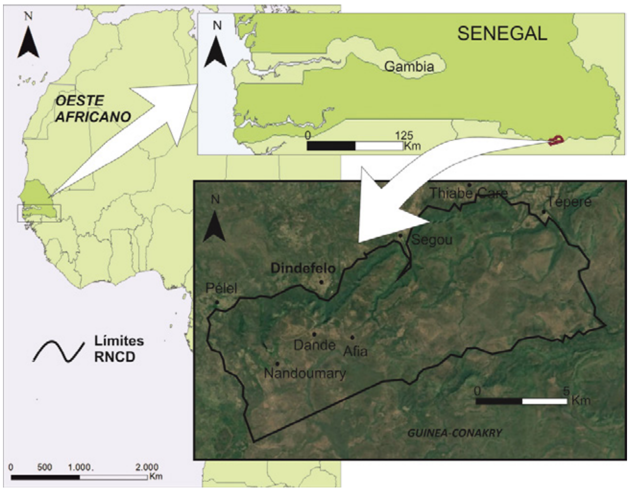

Fig. 1.- Localización de la Reserva Natural Comunitaria de Dindefelo (Senegal).

La reserva presenta una superficie aproximada de 140 km^2, representando un 55% de la superficie total de la Comuna de Dindefelo (CD), que es de 25.200 km^2. Sus límites se encuentran comprendidos entre las siguientes coordenadas:

- Latitud: entre los paralelos 12° 18' 25,67" N y 12° 25' 54,90" N
- Longitud: entre los meridianos 12° 11' 11,78" O y 12° 23' 20,45" O

Marco geológico

La reserva se encuadra en la cuenca sedimentaria de Madina Kouta. Esta cuenca sedimentaria proterozoica se extiende unos 30.000 km^2 entre 4 países: Senegal, Mali, Guinea-Bissau y Guinea-Conakry (Sarr, 2014). Se trata de una cuenca creada por subsidencia dentro del Cratón del África Occidental (CAO), que ha sido activa desde el Mesoproterozoico hasta después de la glaciación del Proterozoico tardío, hace 630 Ma (periodo Ediacárico) (Clauer y Deynoux, 1987). La cuenca se dispone de forma alargada con orientación E-O, profundizando y abriéndose hacia el oeste (Deynoux *et al*., 1993). La columna estratigráfica general (Fig. 2) muestra las formaciones que se describen en los siguientes párrafos y son las que han sido estudiadas en detalle en este trabajo.

Los materiales del basamento pertenecen al CAO, una de las masas continentales que formaron en su momento el supercontinente Rodinia (Li *et al*., 2008). Dicho sustrato se corresponde con secuencias sedimentarias deformadas y metamorfizadas que son posteriormente intruidas por granitos durante el Paleoproterozoico (Kone, 2015). Estos materiales birrimienses están representados en la reserva por mármoles ribeteados, calco-esquistos y granitos rosas, de más de 2.300 Ma (Villeneuve, 1989; Youm *et al*., 2018).

Sobre estas formaciones birrimienses descansa la cobertera sedimentaria de la cuenca de Madina Kouta. La serie de relleno de esta cuenca comienza con el depósito de los materiales del Grupo Segou (1.600 Ma - 900 Ma): conglomerados de base de la Formación Kafori tras la erosión del zócalo birrimiense en un proceso de distensión del cratón (Youm *et al*., 2018); le sigue el depósito de los materiales de la Formación Pélel, que consisten en oosparitas y fangos calcáreos con estromatolitos del Esteniense (Villeneuve, 1989; Youm *et al*., 2018) y, finalmente, se produce una evolución a cuarzoarenitas rojas alternas con lutitas moradas (Formación Dindefelo) del Toniense (Deynoux *et al*., 1993; Youm *et al*., 2018). La serie continúa con el grupo Madina Kouta, que es transgresivo con respecto al grupo Segou. La secuencia sedimentaria de este grupo comienza con una alternancia de limos y carbonatos de la Formación Fongolembi (Sarr, 2014; Dabo *et al*., 2016), seguida por unas areniscas con estratificación cruzada de la Formación Kanta, y culmina con una alternancia de lutitas, areniscas con estratificación cruzada y calizas arenosas de la Formación Dira (Deynoux *et al*., 1993). El conjunto de los depósitos de todas estas formaciones conforma el supergrupo Segou-Madina Kouta.

El depósito del supergrupo Mauritánides da comienzo durante el tránsito Criogénico-Ediacárico, con la Formación Walidiala, discordante con el supergrupo Segou-Madina Kouta. Esta formación consta de conglomerados de matriz calco-limo-arenosa (Youm, *et al*., 2018), lutitas con niveles de areniscas con estratificación cruzada, y areniscas y conglomerados a techo. Esta formación ha sido interpretada como tillitas de una glaciación global. Le sigue, para finalizar el relleno de la cuenca, el grupo Mali, bien representado al norte de Guinea Conakry, con una secuencia granodecreciente retrogradande de lutitas verdes micáceas y no micáceas, dolomitas calcáreas, lutitas moradas y cherts. Toda la serie sedimentaria aparece cortada por diques de rocas subvolcánicas de naturaleza dolerítica (diabasas).

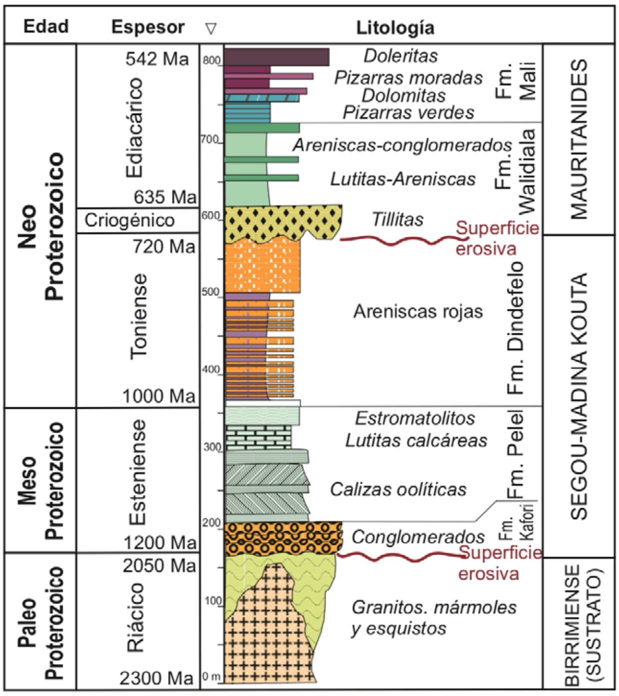

Fig. 2.- Columna estratigráfica general (modificada de Youm *et al*., 2018).

Esta larga historia geológica da origen a una rica diversidad geológica, que constituye el substrato de la biodiversidad de la reserva (Youm *et al*., 2018).

Metodología

En este trabajo se ha realizado un proceso de investigación sobre el terreno de naturaleza sedimentológica en las unidades estratigráficas descritas previamente, y una descripción petrológica de las unidades de carácter no sedimentario (unidades ígneas y metamórficas). De igual modo, se han caracterizado los horizontes de alteración (ferricretas y alteritas) presentes en la superficie del terreno como resultado de un proceso prolongado de edafización en clima tropical.

Usando criterios geológicos, se ha dividido la reserva en unidades territoriales a partir de sus características geomorfológicas, litológicas y de paisaje. Estas unidades han sido representadas en cartografía (Fig. 3). Por otra parte, se han determinado los LIG que se incluyen en cada una de ellas (Fig. 3), tomando como referencia inicial los lugares de interés geoturístico de la RNCD descritos inicialmente por Youm *et al*. (2018). Los LIG propuestos y caracterizados geológicamente fueron valorados desde el punto de vista patrimonial. Para la valoración de los LIG, se tomaron en consideración los criterios de García-Cortés *et al*. (2019), priorizando los valores intrínsecos de los lugares de interés turístico, sobre los extrínsecos (potencial de uso y necesidad de protección), que se relacionan más con el potencial turístico y la gestión del lugar que con el valor científico del LIG (Tabla 1).

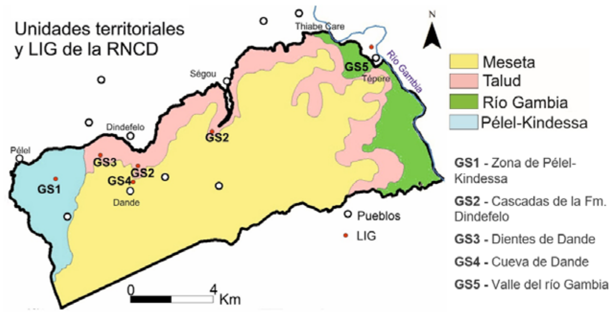

Fig. 3.- Unidades territoriales definidas en la Reserva Natural Comunitaria de Dindefelo (RNCD) y localización de los lugares de interés geológico (LIG) propuestos.

Resultados

Delimitación de unidades territoriales

Las unidades territoriales que se proponen surgen a partir de los elementos geomorfológicos y de relieve principales. Se ha realizado una división de la reserva en 4 unidades generales: la meseta, los taludes, el río Gambia y la zona de Pélel-Kindessa (Fig. 3).

La meseta ocupa unos 8.612 m^2, que representa un 61,5% de la superficie total de la reserva, presenta una dirección preferente NE-SO y es la frontera natural con Guinea-Conakry. Los más de 400 m de altitud sobre el nivel del mar dan lugar al relieve más accidentado del país, y permiten la formación de grandes saltos de agua, como la cascada de Dindefelo, la más alta de Senegal. El substrato de la meseta son cuarzoarenitas rojas bien estratificadas del Toniense (Formación Dindefelo) y cortadas tectónicamente en paralelogramos según dos familias de fallas conjugadas. Sobre estas, la meseta queda recubierta por una laterita ferruginosa que previene la erosión.

El talud corresponde a una zona muy escarpada en casi toda su distribución. Ocupa 2.700 m^2, uniendo la meseta con las zonas más bajas. Conformado principalmente por cuarzoarenitas rojas de la Formación Dindefelo, se observan abundantes depósitos coluviales al pie de los escarpes, formados por los bloques de roca fracturados por diferentes familias de fallas y diaclasas, las mismas que cortan el talud. A través de las fracturas tienen lugar las surgencias de agua donde nacen las cascadas de la zona, manantiales y se originan gargantas donde se desarrolla el bosque de galería, de vital importancia como refugio para la fauna.

El valle del río Gambia es una franja lineal que ocupa el límite oriental de la reserva y es de origen fluvial. El valle constituye la reserva de agua principal de la RNCD y es el abastecimiento de los poblados asentados a su alrededor, como Thiabe Care y Tépere. En contraste con

TIPO	CRITERIO	DESCRIPCIÓN BREVE
INTRÍNSECOS	Representatividad	El lugar ilustra las cualidades del territorio
	Localidad tipo o de referencia	Se trata de un lugar de referencia estratigráfica, paleontológica, etc.
	Nivel de conocimiento científico existente	El lugar es objeto de publicaciones y estudios científicos
	Estado de conservación	Grado de deterioro físico
	Condiciones de observación	Facilidad para observar un rasgo del entorno
	Rareza	Escasez de rasgos similares
	Diversidad geológica	Variedad de elementos de interés geológico en las proximidades
	Espectacularidad o belleza	Calidad visual
	Posibilidades divulgativas y didácticas	Potencial divulgativo o didáctico de un rasgo o si ya se usa para ello
	Posibilidad de realizar actividades recreativas	Cumplimiento de condiciones para realizar actividades de ocio
EXTRÍNSECOS	Infraestructura	Presencia de alojamiento y restauración
	Contexto socioeconómico	Condiciones socioeconómicas de la comarca. Fomento del desarrollo local
	Asociación con otros aspectos del patrimonio natural o cultural	Elementos de interés no geológicos
	Densidad de población	Se asocia al potencial de visitantes y a la probabilidad de actos vandálicos
	Accesibilidad	Facilidad de acceso a visitantes
	Fragilidad	Facilidad de degradación por sus características intrínsecas (litología, tamaño, etc.)
	Cercanía a zonas recreativas	Presencia de zonas recreativas cerca del lugar. Mayor atractivo turístico y mayor probabilidad de vandalismo

Tabla 1.- Criterios de selección de los LIG (modificado de García-Cortés *et al.*, 2019).

los relieves anteriores, la unidad representa un valle con control tectónico, con un fondo de origen aluvial y tramos dominados por lecho rocoso. La pluviometría controla la interrelación entre el río y los acuíferos fisurales laterales, de modo que el río es ganador o perdedor según la estación. Durante la estación seca, el río alimenta los acuíferos (río influente). En la estación de lluvias, el río se nutre de los acuíferos sobresaturados (río efluente).

La zona de Pélel-Kindessa se extiende en los alrededores del poblado homónimo. Abarca el sector noroccidental de la RNCD y los valles de Walidiala y Nandumary, entre los municipios de Pélél y Tanague. Esta zona presenta un interés particular desde el punto de vista geológico. Si bien, se encuentra en su mayoría en una zona de alta pendiente que podría calificarse como talud, los materiales que constituyen su extensión son diferentes al resto de taludes y litológicamente más diversos, aportando información sobre grandes eventos de la historia de la Tierra y, particularmente, de la reserva. Los taludes los conforman las oosparitas de la Formación Pélel y las tillitas de la Formación Walidiala, en contraste con las cuarzoarenitas rojas que levantan la meseta en el resto de la RNCD.

Determinación de los lugares de interés geológico (LIG)

La selección de recursos para el turismo geológico se ha realizado a partir de los lugares de interés turístico preestablecidos de la zona, siendo éstos los que se proponen como lugares remarcables. Como resultado, se han obtenido los 5 LIG (Fig. 3) que se describen a continuación.

GS1 - Zona de Pélel-Kindessa. Los alrededores del municipio de Pélel presentan un particular interés geológico por su singularidad y diversidad geológica. La superficie abarcada por este LIG se solapa con la de la unidad territorial homónima. En este sector aflora el zócalo birrimiense, el conjunto de rocas más antiguas presentes. Está constituido por un cinturón metamórfico de más de 2.300 Ma de calco-esquistos (Fig. 4A) y mármoles ribeteados (Fig. 4B), cortados por granitos rosas (Fig. 4C). Los esquistos se encuentran fuertemente plegados y su extensión lateral en afloramiento es discontinua. El granito tiene una coloración rosácea, el tamaño de grano es grueso, distinguiéndose minerales como cuarzo, plagioclasa, biotita, y otros en menor cantidad, como el circón.

Fig. 4.- Materiales del zócalo birrimiense de la unidad territorial GS1 - Zona de Pélel-Kindessa. A) calco-esquistos; B) mármoles; C) granito rosa.

Los mármoles ribeteados y esquistos del zócalo serían el resultado de la deformación producida previa al emplazamiento de una gran cámara magmática, constituyendo las rocas encajantes de la misma. El enfriamiento lento del magma ácido contenido en esta cámara da lugar a la aparición del granito rosa.

Discordantemente sobre ellos se sitúan los materiales de las Formaciones Kafori y Pélel. La Formación Kafori está conformada por un conglomerado matriz-soportado (localmente clasto-soportado), con cantos redondeados a sub-redondeados. Los cantos pertenecen a fragmentos de roca de las formaciones birrimienses en una matriz carbonatada (Fig. 5A). La secuencia de rocas que conforman la Formación Pélel se compone de oosparitas y fangos calcáreos con estromatolitos. El tamaño de grano va de fino en los lodos, a tamaño arena media-gruesa en las oosparitas. Destacan las estructuras sedimentarias, principalmente en las oosparitas, observándose laminaciones paralelas con ritmos cíclicos originados por la alternancia de mareas vivas y muertas (tidalitas) (Fig. 5B), y estratificaciones cruzadas que pueden presentar, o no, estas ritmitas mareales.

La Formación Kafori es el conglomerado basal del primer depósito de la cuenca de Madina Kouta. La litología de la Formación Kafori sugiere un carácter continental y un origen aluvial. Según Sarr (2014), la falta de estructuras preservadas y la heterogeneidad del conglomerado indican un ambiente de depósito proximal.

El carácter oolítico carbonatado de la Formación Pélel y sus estructuras sedimentarias permiten interpretarla como una llanura perimareal carbonatada. En las costas

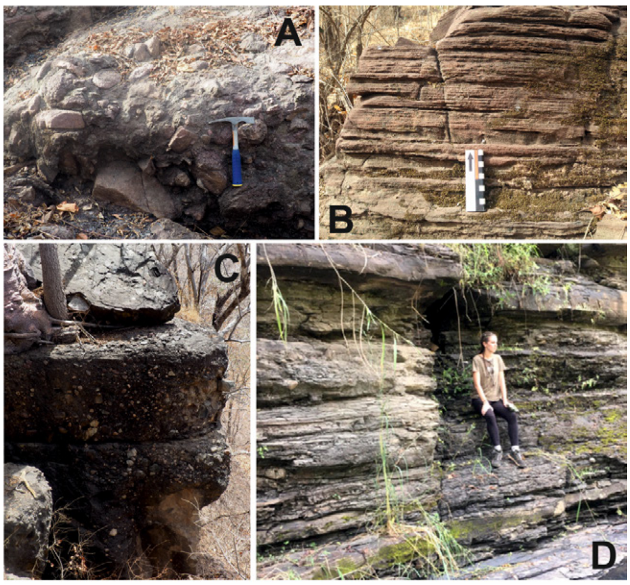

Fig. 5.- Primer relleno sedimentario de la cuenca de Madina Kouta. A) conglomerado basal de la Formación Kafori; B) oosparitas con tidalitas de la Formación Pélel; C) tillita de la Formación Walidiala; D) tillitas laminadas

calcáreas, donde hay falta de aportes terrígenos, la calcita precipita preferentemente en la zona submareal (*carbonate factory*), desde donde puede ser erosionada y distribuida como clastos sedimentarios dentro de la zona intermareal (James, 1984). La presencia de tidalitas sugieren un medio somero, como podría ser una llanura de marea. La presencia, a techo, de estromatolitos también es diagnóstica de un medio poco profundo desarrollado en un clima cálido tropical, con actividad de bacterias cianofíceas.

La Formación Walidiala se dispone mediante una discordancia erosiva sobre el Grupo Segou. Aflora un conglomerado masivo matriz-soportado a clasto-soportado, sin estructura interna, con bloques de tamaño variable, de milimétricos a métricos, poco maduros, pertenecientes a los materiales precedentes del zócalo birrimiense, y las Formaciones Pélel y Dindefelo (Fig. 5C). La matriz está compuesta por arcillas rojas. A techo, los estratos pasan de presentar estructura masiva a laminada, con intercalaciones de lutitas (Fig. 5D). Esta brecha, que conforma un mirador sobre el valle de Walidiala, se interpreta como tillitas de un periodo glacial del Neoproterozoico tardío entre 630 y 595 Ma (Clauer y Deynoux, 1987). Formaciones equivalentes constituidas por tillitas son correlacionables por todo el CAO y forman parte, junto con los carbonatos y los cherts de la formación Mali que se superponen, de la denominada 'Tríada Glacial' (Miningou *et al*., 2011).

Finalmente, se observa el emplazamiento de doleritas y basaltos, evidencia de la actividad volcánica más reciente en la región, cortando la secuencia sedimentaria en diversas zonas de la RNCD. Los basaltos se han observado a techo de las oosparitas, en disposición horizontal, intruyendo a modo de sills (Fig. 6A). Las doleritas, por el contrario, cortan en sentido oblicuo o vertical (diques) a las Formaciones de Dindefelo y Mali, al oeste de la reserva, dando lugar localmente a afloramientos de berrocales (Fig. 6B).

A la diversidad geológica de Pélel, se le añade el valor paisajístico de los valles de Walidiala y Nandoumary (criterio belleza), y el valor botánico del ecosistema de bosque claro. Es un lugar que presenta también valor cultural a través del mito sobre 'el tronco de Pélel' (asociación con otros aspectos patrimoniales), que habla de un tesoro escondido en un árbol, lleno de riquezas y que aparece aleatoriamente ante los caminantes de la zona. La leyenda sostiene que aquellos que encuentran el tesoro, no encuentran la llave, mientras que aquellos a los que se les presenta la llave, no son capaces de hallar el cofre. Por otra parte, numerosos grupos de estudiantes universitarios vienen a la RNCD cada año, y buena parte de las sesiones de trabajo de campo se realizan aquí (criterio posibilidades divulgativas y didácticas). El conjunto de todos estos aspectos hace de este lugar un potencial LIG fundamental dentro de la RNCD.

GS2 - Cascadas de la formación Dindefelo. Las cuarzoarenitas de la Formación Dindefelo conforman la mayor parte del talud de la meseta al norte de la reserva (criterio representatividad), caracterizada por importantes cascadas y saltos de agua que dan lugar a pozas aprovechadas por la población para encuentros sociales, para sobrellevar las altas temperaturas de los meses de abril y mayo, y por los grupos de mujeres locales, que lavan la ropa en los cursos de agua que descienden de las pozas hacia cotas más bajas. Estas cascadas (Fig. 7), además de presentar un valor paisajístico (criterio belleza) y sociocultural (con posibilidad de actividades recreativas y de ocio), dan lugar al desarrollo de un bosque galería, un oasis botánico para la fauna durante la época de sequía, especialmente, para las especies en peligro de extinción de Senegal y el oeste africano (asociación con otros aspectos naturales).

La formación Dindefelo, conformada por una alternancia de lutitas violetas y cuarzoarenitas rojas con glauconita, presenta una gran diversidad de estructuras sedimentarias. El tamaño de grano varía de arena fina a gruesa, observándose localmente niveles microconglomeráticos. Las formas de fondo principales incluyen *ripples* simétricos,

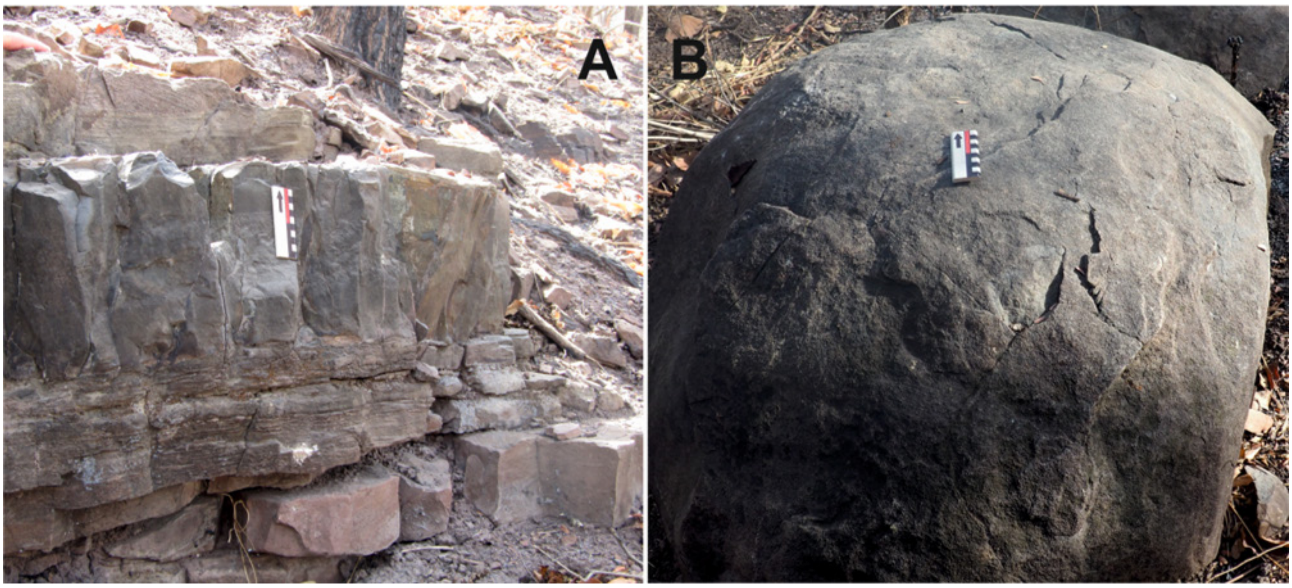

Fig. 6.- Evidencias de la actividad volcánica más reciente en la RNCD. A) sill de basalto encajado en las oosparitas de la Formación Pélel; B) berrueco de dolerita.

Fig. 7.- Diferentes cascadas con salto excavado en la Formación Dindefelo.

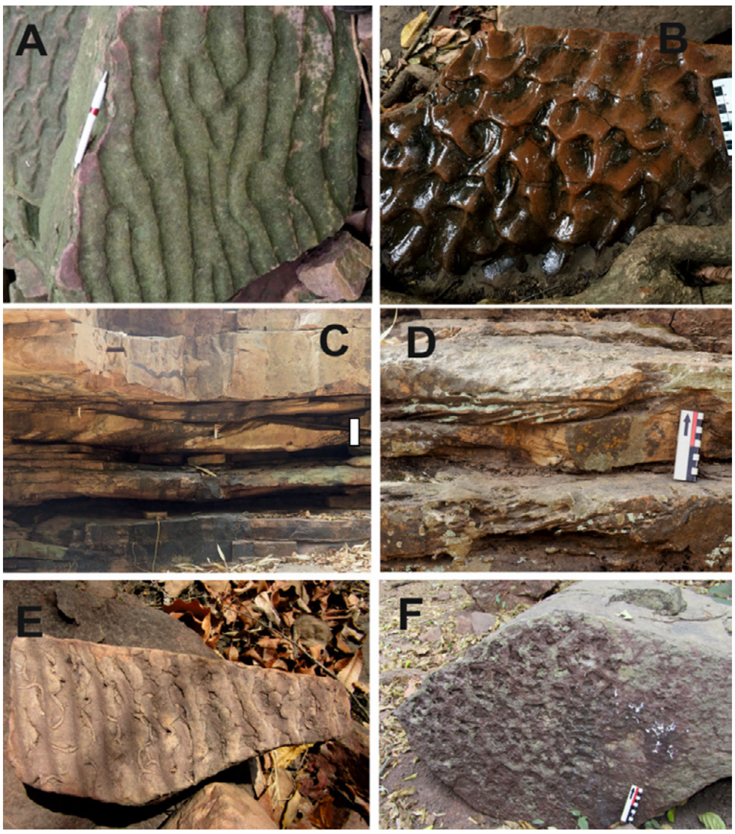

Fig. 8.- Diferentes estructuras de la Formación Dindefelo. A) *ripples* asimétricos; B) *ripples* linguoides; C) dunas; D) *herringbone*; E) *ripples* con bioturbaciones; F) tapiz bacteriano.

asimétricos (Fig. 8A), linguoides (Fig. 8B), trenes de *ripples* de interferencia, dunas (Fig. 8C) y barras de arena; abundan las formas mareales como *herringbones* (Fig. 8D) y *tidal bundles*. Adicionalmente, se observan numerosas estructuras biogénicas que denotan la presencia de organismos complejos ya en el Neoproterozoico (Fig. 8E), además de una gran variedad de tapices bacterianos (Fig. 8F), algo singular en esta formación respecto al resto del registro de ese periodo (criterios rareza y estado de conservación).

Deynoux *et al.* (1993) describen variaciones periódicas de energía que caracterizan a medios de dominio mareal. La interpretación de este trabajo defiende que la presencia de bioturbaciones, tapices bacterianos, grietas de desecación, formas de fondo 2D y 3D, estratificaciones cruzadas, *flaser, wavy*, y *lenticular bedding*, *tidal bedding* y *tidal bundles*, son característicos de la acción de corrientes de marea en los diferentes submedios de las llanuras mareales, de acuerdo con los criterios establecidos por Davis *et al.* (2012).

El valor geopatrimonial de las cascadas, especialmente la gran cascada de Dindefelo, es el afloramiento de una secuencia completa de los depósitos costeros de la formación homónima (posibilidades didácticas y divulgativas).

La Gran Cascada tiene su origen en la meseta de Dande, donde se produce una surgencia de aguas subterráneas que caen en catarata por el acantilado de la meseta.

GS3 - Dientes de Dande. En la meseta, al noroeste del pueblo de Dande, se encuentra uno de los paisajes más espectaculares de la reserva (criterio espectacularidad), conformado por pilares en forma de prisma de base rectangular, de ahí la nomenclatura de "dientes", esculpidos en las cuarzoarenitas rojas de la Formación Dindefelo (Fig. 9A). Este lugar de interés geomorfológico es resultado de una tectónica regional extensional acompañada de la acción erosiva de las aguas superficiales (posibilidades didácticas y divulgativas). Bloques decimétricos cortados por estas familias de diaclasas que definen los "dientes", acaban al pie de los escarpes mediante caída directa, fuente de riesgos geológicos. Así, dan lugar a abanicos de derrubios. Las estructuras presentes en estos bloques son muy diversas y son aquellas propias de la Formación Dindefelo, anteriormente descritas.

colores ocres. Este horizonte puede igualmente alcanzar varios metros de espesor. En algunas zonas de la meseta, donde la ferricreta ha sido erosionada por completo aflora en superficie la alterita no cementada. Allí se desarrolla un suelo más rico en materia orgánica, donde aparecen termiteros de tipo "champiñón" (Fig. 10B).

Al norte del poblado de Dande, se observa un corte en la laterita acompañado de una importante depresión topográfica, dando lugar a un brusco cambio en la vegetación, que pasa a ser bosque galería (Fig. 10C). Se trata de una cueva excavada en las alteritas. En su origen, la cueva se habría originado de forma natural por diferenciación de resistencia de materiales, siendo la alterita más lábil y fácil de erosionar que la costra férrica superior. Sin embargo, además de la erosión natural, el ser humano ha realizado excavaciones en la cueva para extraer el azufre de la alterita y fabricar pólvora (criterio relación con otros aspectos patrimoniales). Así, esta cueva presenta una gran relevancia histórica. En ella se encuentra el origen del pueblo de Dan-

Fig. 9.- Paisaje en la meseta de la RNCD. A) panorámica de los Dientes de Dande; B) los Pequeños Dientes.

La geología no es la única protagonista aquí, ya que los Dientes de Dande conforman un mirador hacia la sabana y el bosque claro del valle de Condodji, entre Dindefelo y el valle de Nandoumary. Hacia el este, existe otra morfología similar, de menor escala, en una zona cercana conocida como los 'Pequeños Dientes' (Fig. 9B) y que presenta los mismos valores en cuanto a potencial patrimonial.

GS4 - Cueva de Dande. La meseta se encuentra recubierta por un horizonte de laterita compacta, debido a la cementación de ferricreta de un intenso color rojo, que no permite un buen desarrollo de plantas de gran envergadura (Fig. 10A). Por tanto, el bioma es de tipo sabana, con cobertura arbórea pobre y escasa penetración de las raíces. Este horizonte laterítico puede alcanzar en algunos lugares potencias superiores a los 5 m. Bajo la ferricreta compacta se encuentra un segundo horizonte conformado por una alterita mucho más arcillosa y de

de, cuando en 1945 los hermanos Manga Kouladio Diallo y Manga Binté Vero Diallo llegaron huyendo del yugo del colonialismo en Guinea-Conakry. Posteriormente, la cueva ha sido refugio también de los animistas del pueblo Bédik y Bassari en su intento por escapar de la islamización llevada a cabo por el rey de Labé, también en Guinea. Tradicionalmente, la gruta ha servido como escenario de numerosos eventos del folclore local (Fig. 10D), lleno de misticismo, por lo que posee también un importante patrimonio inmaterial asociado. La cueva se encuentra a escasos metros del pueblo de Dande, donde se encuentra el único campamento turístico de toda la meseta (el *plateau)*, lo que facilita las visitas (criterio infraestructuras logísticas).

*GS5 - Valle del río Gambia***.** El río Gambia es el principal curso de agua de la RNCD. Este río transfronterizo tiene sus accesos más populares a orillas de los pueblos de Thiabe Care y Tépere, y presenta un gran valor ecológico,

Fig. 10.- Imágenes en la zona de la Cueva de Dande. A) laterita sobre la meseta; B) termitero champiñón; C) perfil diferencial de la cueva: a muro, las alteritas y, a techo, la ferricreta; D) elementos del folclore local en la cueva.

hidrogeológico, y turístico. Como recurso hídrico, se trata de la reserva de agua principal de la zona. Como punto de agua permanente, el río Gambia representa el refugio de diferentes especies faunísticas durante el estío, y el hábitat de hipopótamos y una gran diversidad de aves.

El curso del río está controlado por fallas conjugadas con direcciones NO-SE y NE-SO, generando un recorrido bastante rectilíneo, pero con algunos meandros. Como se muestra en la Figura 11A, en los tramos de lecho rocoso afloran los granitos rosas del zócalo birrimiense (ya descritos para la zona de Pélel), redondeados por la erosión del agua, y que cuando desciende el nivel de agua, permiten la formación de pozas naturales usadas para ocio y actividades tradicionales (criterio posibilidad de realizar actividades recreativas), como la pesca con red y el lavado de telas por los grupos de mujeres de la zona. En los márgenes del río se ha observado la base de la formación Dindefelo y las estructuras sedimentarias características de esta formación (Fig. 11B).

En Thiabe Care se encuentra el campamento turístico más descentralizado (criterio infraestructura logística). Además, una laterita de edad paleozoica en Tépere da lugar a la leyenda del "cazador persiguiendo a la res", ya que sobre la roca se observan secciones de clastos similares a pisadas de personas y huellas de ganado (Fig. 11C) que, según la tradición oral, pertenecen a uno de los primeros hombres que habitaron el lugar (criterio asociación con otros aspectos patrimoniales). Estas marcas le dan nombre al pueblo en la lengua local.

Propuesta de gestión de los LIG en la RNCD

La RNCD carece de medidas específicas para la preservación del patrimonio geológico. Algunas normas internas de la reserva, establecidas en el Plan de Gestión aprobado el 29 de junio de 2021 y en vigor hasta 2026, apelan directamente a algunos de los LIG propuestos en las medidas establecidas para la preservación de la biodiversidad y lugares de interés turístico que se encuentran en zona de reserva integral.

En los alrededores de la Cascada de Dindefelo, LIG más visitado y que sufre la mayor presión turística, se permite un máximo de 25 personas, mientras que sólo 10 personas pueden bañarse al mismo tiempo en la poza. Así mismo, se prohíbe escuchar música, gritar y preparar té o prender carbón, prácticas habituales de la población que perturban no solo a la fauna, sino que dificultan la experiencia sensorial intangible del turista. Tampoco está permitido realizar *grafitis* o pintadas en las paredes rocosas de la cascada. La dirección de la RNCD estableció vigilantes en el camino de la cascada para controlar el aforo y la compraventa de tiques.

La reserva integral ha sido señalizada en los caminos que la atraviesan. Se diseñó e instaló una cartelería indicando las normas a seguir en estas áreas (Fig. 12A), desconocidas en general por la población. En el plan de gestión se establecieron sanciones para aquellos infractores de la normativa, mientras que los ecoguardas se encargan de supervisar, por toda la reserva, el cumplimiento de lo establecido en el plan de gestión.

Asimismo, se han realizado recomendaciones a la dirección de la RNCD que conciernen directamente a la conservación del patrimonio geológico. Estas indicaciones consisten en la prohibición de recogida de muestras y picar y/o deteriorar, de cualquier manera, las superficies rocosas. También se sugiere, para mayor seguridad, no desviarse de los caminos establecidos e ir siempre acompañado de un guía turístico local.

En la promoción y divulgación de la geología y del

Fig. 11.- Imágenes del valle del río Gambia. A) afloramiento de granitos rosas del zócalo birrimiense en los márgenes del Gambia (abajo a la derecha); B) afloramiento de la base de la Formación Dindefelo; C) supuesta huella de uno de los primeros habitantes de Tépere.

geoturismo de la RNCD y del desarrollo de su potencial, se muestra en la Figura 12B la guía geológica de divulgación que se redactó sobre la geología de la reserva para el turista. Estas guías podrán ser vendidas en el centro de visitantes y permitirán un pequeño beneficio, junto con la puesta en valor del patrimonio geológico, tan desconocido del lugar. De forma complementaria, se ha elaborado una cartelería didáctica sobre la diversidad de materiales presentes en la reserva, las estructuras sedimentarias y biogénicas principales y su interpretación, ubicada en el centro de visitantes. Además, se ha habilitado una sala del ecomuseo para la geología, con muestras de los diferentes tipos de rocas y estructuras reflejadas en los paneles. También se han colocado paneles en el inicio de las rutas turísticas principales, cuyo contenido describe lo que se observa a lo largo del recorrido en relación con la fauna, la flora, la geología y la cultura o el paisaje (Fig. 12C). Finalmente, se ha señalizado la ruta hacia la reserva desde la carretera de Kédougou, a 37 km de Dindefelo. Se han colocado 4 paneles direccionales, el primero a los 37 km (Kédougou), luego a 12 km (cruce de Thiabe Care), 5 km (Segou) y 1 km. Un quinto cartel fue colocado en la entrada del centro de visitantes para darle mayor visibilidad a la reserva.

Discusión

Una limitación para el establecimiento de nuevos LIG de uso turístico es que algunas zonas interesantes de la RNCD se encuentran en zona de reserva integral, como la cascada de Segou o la “*Petite Cascade*”. Estas zonas están cerradas al uso público, y son de uso exclusivo para la investigación y conservación de especies biológicas en peligro de extinción.

Algunos LIG potenciales de la RNCD son: el valle de Nandoumary, las cascadas de Badiari, la Petit Cascade, la cascada de Segou y su valle, el valle de Condodji y el antiguo asentamiento de Pélel, o las discontinuidades geológicas. Los contactos entre formaciones tienen potencial didáctico, ya que evidencian largos periodos de no depósito y/o de erosión, e informan sobre la transición entre una formación y otra. En la RNCD los contactos a valorizar podrían ser el del zócalo birrimiense con el supergrupo Segou-Madina Kouta y el del supergrupo Segou-Madina Kouta con el grupo Mauritánides (Youm *et al*., 2018).

Para el análisis de los LIG presentados en este trabajo, no se ha realizado un inventario completo ni se han agotado las posibilidades de seleccionar nuevos lugares, sino que se ha puesto en valor la geología de los puntos de interés turístico previamente establecidos con otros criterios. Sería interesante hacer una evaluación de otras zonas de la reserva para completar el inventario de lugares de interés geológico y aumentar el conocimiento sobre el patrimonio geológico y natural de esta región. Asimismo, se pueden evaluar las zonas protegidas para que, en caso de que cambie el régimen de protección, se pueda mejorar la gestión turística de las mismas.

El geoturismo está cada vez más considerado en la planificación del uso público de los espacios naturales protegidos. Así, la gran riqueza geológica de la RNCD aporta otro valor más a la reserva, atrayendo a un público diferente. Para una mejor experiencia turística, los guías turísticos locales se encargan de explicar curiosidades sobre la fauna, la flora, la cultura, o el paisaje. En el transcurso de ejecución del proyecto en el que se encuadra este trabajo, se rea-

Fig. 12.- Ejemplos de paneles para la gestión de los LIG en la RNCD. A) normas implantadas para las áreas de reserva integral; B) guía divulgativa sobre la geología de la reserva; C) colocación de panel didáctico con información sobre la ruta.

lizó una sesión de formación que asentaron las bases del conocimiento sobre las características geológicas de la reserva, aplicado al patrimonio geológico de los lugares más visitados turísticamente.

De cara al futuro, una prolongación en el tiempo y profundización en esta materia podrían afianzar estos conocimientos y darían la capacidad de realizar explicaciones más detalladas de las características de la RNCD. Lo que sería concordante con el proyecto llevado a cabo por el Ministerio de Geología y Minas de Senegal de comenzar una Red Nacional de Geoparques y su propuesta de calificar Dindefelo como Geoparque piloto.

Existe una falta de infraestructuras en ciertos lugares de interés potencial. En consecuencia, el turismo se concentra en Dindefelo, Dande y Thiabe Care, donde la capacidad de carga de turistas es mayor (criterio densidad de población). Esto hace que el desarrollo de los pueblos más aislados sea complicado, ya que el turista invierte solo en lugares con infraestructura, donde sea posible comunicarse en francés, y pueda hospedarse con comodidad.

Los accesos a ciertos LIG son complicados, como los puntos de interés sobre el *plateau.* El ascenso a la meseta presenta una pendiente importante en las rutas peatonales, y las rutas con posibilidad de ascenso en vehículo (generalmente en moto), no cumplen ningún estándar de seguridad vial, no están asfaltadas y están cubiertas de coluviones.

A pesar del respaldo jurídico de la RNCD, las directivas y reglamentos definidos en el Plan de Gestión, que otorgan protección a la reserva, no siempre se aplican. No hay un plan de seguimiento real del cumplimiento de las reglas establecidas para los lugares turísticos, además de la presión que ejerce la sobrepoblación sobre éstos durante los fines de semana, vacaciones y fiestas locales, acentuadas por la inminente apertura de una ruta asfaltada para acceder a la zona.

Una alta diversidad geológica no implica que los elementos que la constituyen formen parte del patrimonio geológico (Carcavilla *et al*., 2008). Sin embargo, este trabajo muestra que la RNCD presenta un rico patrimonio geológico, representativo de los eventos geológicos ocurridos durante 1.800 Ma de historia geológica del Oeste Africano. Esto se debe, entre otras razones, a la existencia de una diversidad geológica regional y local considerable.

Los elementos geológicos constituyentes de esta diversidad geológica presentan un elevado interés didáctico y científico, como lo demuestran las estancias de alumnos universitarios de varias universidades para la realización de las prácticas de campo de geología sedimentaria (Youm *et al*., 2018). La RNCD acoge cada año a investigadores en la zona, y se han realizado numerosos trabajos académicos en diferentes zonas de la región de Kédougou (tesis, trabajos fin de máster/grado, informes, etc.). Los valores pedagógico y científico se relacionan estrechamente con la biodiversidad y la cultura, nexo necesario para Brilha (2016) en la consideración del patrimonio geológico.

Conclusiones

La RNCD presenta numerosos puntos fuertes en relación con el ecoturismo, concretamente, dentro de la rama del geoturismo. En relación con el estudio del patrimonio geológico de la zona: a) se proponen los 5 puntos principales de interés turístico de la RNCD como lugares de interés geológico, tanto por sus cualidades intrínsecas, como extrínsecas; b) los LIG seleccionados son representativos de los eventos geológicos ocurridos en el cratón durante el Proterozoico; c) el desarrollo de una normativa específica para la gestión y conservación de los LIG de la reserva es necesaria; y d) la investigación geológica debe continuar para seguir con el proceso de desarrollo del conocimiento sobre el patrimonio geológico de la RNCD, aún escaso.

Con respecto al futuro del geoturismo en la zona, se concluye que la formación a los guías en materia de geología ha permitido la introducción y apropiación de mucha información tanto de geología general, como específica de la historia geológica de la reserva. La cartelería puede seguir desarrollándose y está concebida como soporte visual de las explicaciones del guía local. Finalmente, los accesos tanto a la RNCD como a los LIG deben habilitarse, así como debe cuidarse la infraestructura logística para ofrecer un servicio adecuado a las expectativas del turista.

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Referencias

Brilha, J., 2016. Inventory and quantitative assessment of geosites and geodiversity. The European Association for Conservation of the Geological Heritage. Geoheritage, 8: 119-134. https://doi.org/10.1007/s12371-014-0139-3

Carcavilla, L., 2012. Geoconservación. Madrid: IGME-Catarata.

Carcavilla, L., Díaz Martínez, E., Erikstad, L., García Cortés, A., 2013. Valoración del patrimonio geológico en Europa.

Boletín Paranaense De Geociencias, 70: 28-40. https://doi.org/10.5380/geo.v70i0.31501

Carcavilla, L., Durán Valsero, J.J., López Martínez, J., 2008. Geodiversidad: Concepto y relación con el patrimonio geológico. VII Congreso Geológico De España, Geo-Temas 10: 1299-1303.

Carcavilla, L., Durán Valsero, J.J., López Martínez, J., 2008. Patrimonio geológico y geodiversidad: Investigación, conservación y relación con los Espacios Naturales Protegidos. IGME, Serie Cuadernos del Museo Geominero, 7, Madrid: 360 p.

Clauer, N., Deynoux, M., 1987. New information on the probable isotopic age of the late proterozoic glaciation in West Africa. Precambrian Research, 37: 89-94. https://doi.org/10.1016/0301-9268(87)90072-6

Dabo, M., Aifa, T., Baratoux, D., Diatta, F., Ndiaye, M., Van Lichtervelde, M., 2016. Guide d'excursion Picg638, 1er colloque du programme Picg638, Dakar, Senegal: 50.

Davis, R.A., Dalrymple, Jr., Dalrymple, R.W., 2012. Principles of Tidal Sedimentology. Springer, 35. https://doi.org/10.1007/978-94-007-0123-6

Deynoux, M., Duringer, P., Khatib, R., Villeneuve, M., 1993. Laterally and vertically accreted tidal deposits in the Upper Proterozoic Madina-Kouta Basin, South Eastern Senegal, West Africa. Sedimentary Geology, 84: 179-188. https://doi.org/10.1016/0037-0738(93)90054-9

Dóniz-Páez, F.J., Becerra Ramírez, R., Serrano Patón, M., Báez Hernández, M., 2020. Geodiversidad, geopatrimonio y geoturismo en los Espacios Naturales Protegidos del geoparque volcánico de El Hierro (Canarias, España). Cuadernos Geográficos de la Universidad de Granada, 60, 2: 52-71. https://doi.org/10.30827/cuadgeo.v60i2.15572

Farsani, N.T., Cohelo, C., Costa, C., 2010. Geotourism and geoparks as novel strategies for socio-economic development in rural areas. International Journal of Tourism Research, 13: 68-81. https://doi.org/10.1002/jtr.800

James, N.P., 1984. Shallowing-uppwards sequences in carbonates. Walker, R. G. Ed, Facies Models, Geosci. Can. Reprint, 1: 213-229.

García-Cortés, A., Vegas, J., Carcavilla, L., Díaz-Martínez, E., 2019. Bases conceptuales y metodología del Inventario Español de Lugares de Interés Geológico (IELIG). Madrid: Instituto Geológico y Minero de España, 106 p.

Hilario, A., Carvavilla, L., Belmonte, A., 2017. Propuesta de standard metodológico para la elaboración de inventarios de lugares de interés geológico (LIG) en el caso la red global de geoparques. El caso del geoparque mundial de la unesco de costa vasca. Madrid: Instituto Geológico y Minero de España. Cuadernos del Museo Geominero, 21: 103-108.

Hose, T.A., Markovik, S.B., Komak, B., Zorn, M., 2011. Geotourism-A shot introduction. Acta geographica Slovenica, 51-2: 339-342. https://doi.org/10.3986/AGS51301

Kone, J., 2015. Signification de l'héritage structural et métamorphique de la série metasédimentaire encaissant du pluton de granite de Saraya (Sénégal Oriental). (Craton Ouest Africain, 2.2 - 2.0 Ga): Implications géodynamiques. Mémoire de Master II: 44 p.

Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., Vernikovsky, V., 2008. Assembly, configuration and break up history of Rodinia: A Synthesis. Precambrian Research: 179-210. https://doi.org/10.1016/j.precamres.2007.04.021

Miningou, Y.W.M., Affaton, P., Bamba, O., Lompo, M., 2015. Mise en evidence d'une triade glaciaire Néoprotérozoïque et d'une molasse dans la région du Beli, bassin du Gourma, Nord-Est Burkina Faso. Journal des Sciences et Technologies: 65-80.

Palacio Prieto, J.L., Rosado González, E.M., Martínez Miranda, G.M., 2018. Geoparques. Guía para formación de proyectos. Unam. Instituto de Geografía: 13-14. https://doi.org/10.14350/gsxxi.tu.22

Palacio Prieto, J.L., Vázquez Selem, L., 2015. Geodiversidad y geopatrimonio, La naturaleza y su interacción con el ser humano, Cap, 6: 102-114.

Sarr, R., 2007. Geologie des bassins sédimentaires du Sénégal. Informe inédito. Fst/Ucad. Universite Cheikh Anta Diop. Faculté des Sciences et Techniques. Département de Géologie, 2014, 37 p.

UICN, 2020. The UICN Red List of threatened species. Version 2020-2. https://Www.Iucnredlist.Org

Villeneuve, M., 1989. The geology of the Madina-Kouta basin (Guinea-Senegal) and its significance for the geodynamic evolution of the western part of the West African Craton during the upper Proterozoic period. Precambrian Research, 44: 305-322. https://doi.org/10.1016/0301-9268(89)90050-8

Wimbledon, W.A., Smith-Meyer, S., 2012. Geoheritage in Europe and its conservation, 405. Oslo: ProGEO.

Youm, C.I., Errami, E., Sow, E., 2008. Neoproterozoic Dindefelo waterfall geosite (DCNR, Bassari Country, Eastern Senegal): Biodiversity and geodiversity between conservation and valorisation. Journal Of Chemical, Biological and Physical Sciences, 8 (3): 197-224.

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Díaz Martínez, E., 1988. El Cretácico Inferior del sector de Jubera (norte de la Sierra de Los Cameros, La Rioja). II Congreso Geológico de España, Comunicaciones, 1: 67-70.

Lobo, F.J., Hernández-Molina, F.J., Somoza, L., Díaz del Río, V., 2001. The sedimentary record of the post-glacial transgression on the Gulf of Cadiz continental shelf (Southwest Spain). Marine Geology, 178: 171-195. https://doi.org/10.1016/S0025-3227(01)00176-1

Ortega Gironés, E., Gil Ibarguchi, J.I., 1983. La Unidad de Malpica-Tuy. En: Libro jubilar, J.M. Ríos. Geología de España, Tomo I, (J. Comba, Ed.). IGME, Madrid, 430-440.

Parra, J., 2001. Análisis paleoambiental de los sistemas continentales y el vulcanismo asociado del Neógeno del Valle del Cajón en los Andes Occidentales (Catamarca, República Argentina). Tesis Doctoral, Univ. Huelva, 272 p.

Woodroffe, C.D., 2002. Coasts. Cambridge University Press, New York, 623 p. https://doi.org/10.1017/CBO9781316036518

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Díaz Martínez, E., 1988. El Cretácico Inferior del sector de Jubera (norte de la Sierra de Los Cameros, La Rioja). II Congreso Geológico de España, Comunicaciones, 1: 67-70.

Lobo, F.J., Hernández-Molina, F.J., Somoza, L., Díaz del Río, V., 2001. The sedimentary record of the post-glacial transgression on the Gulf of Cadiz continental shelf (Southwest Spain). Marine Geology, 178: 171-195. https://doi.org/10.1016/S0025-3227(01)00176-1

Ortega Gironés, E., Gil Ibarguchi, J.I., 1983. La Unidad de Malpica-Tuy. In: Libro jubilar, J.M. Ríos. Geología de España, Tomo I, (J. Comba, Ed.). IGME, Madrid, 430-440.

Parra, J., 2001. Análisis paleoambiental de los sistemas continentales y el vulcanismo asociado del Neógeno del Valle del Cajón en los Andes Occidentales (Catamarca, República Argentina). Doctoral Thesis, Univ. Huelva, 272 p.

Woodroffe, C.D., 2002. Coasts. Cambridge University Press, New York, 623 p. https://doi.org/10.1017/CBO9781316036518

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