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RESEARCH ARTICLE

Uplifted marine terraces by active coastal tectonic deformation along the east of Algiers: implications for African and European plate convergence and sea-level curves

Terrazas marinas levantadas por deformación tectónica costera activa a lo largo del este de Argel: implicaciones para la convergencia de las placas africana y europea y las curvas del nivel del mar

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Key points

The Algiers region is characterized by a relatively high tectonic movement that leads to the formation of marine terraces.

Natural shoreline structures are contemporaneous on the Eastern Algiers shore, controlled by their elevation and flat surfaces.

The objective of measuring the elevation of marine terraces is to know the uplift at which the Zemmouri area is affected.

ABSTRACT

Marine terraces are geological features composed of elevated, flat surfaces and steep slopes. The evolution of these terraces is largely influenced by active coastal tectonic deformation. This study investigates the uplift of marine terraces along the east coast of Algiers and its implications for the African and European plate convergence and sea-level curves. The objective of studying marine terraces in the Zemmouri area is to gain a deeper understanding of the evolution of the Earth's coastlines and how they have been shaped over time by natural processes such as sea level changes, tectonic activity, geomorphic parameters, and erosion. Marine terraces provide valuable information about the history of sea level changes and the rate of tectonic uplift or subsidence of the coastal areas. Secondary data sources, including qualitative information and high-resolution satellite imagery (SRTM 30 m and ALOS 12.5 m), were used to analyze the impact of sea level on marine terraces. Fieldwork using GPS and altimeter measurements at the site of the Mw=6.8 Zemmouri earthquake that occurred on May 21, 2003, revealed the presence of two well-preserved marine terraces, which serve as important markers for measuring the long-term fault slip rate. The analysis highlights the significance of active coastal tectonic deformation in shaping the coastlines. This research offers new insights into the ongoing processes of plate convergence and sea level change along the east coast of Algiers, contributing to our overall comprehension of coastal evolution and the potential for seismic hazards in the region.

Keywords: Marine terraces; Active coastal tectonic; Plate convergence; Earthquake; Geomorphic markers.

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Puntos clave

La región de Argel se caracteriza por un movimiento tectónico relativamente elevado que conduce a la formación de terrazas marinas.

Las estructuras naturales del litoral son contemporáneas en la costa oriental de Argel, controladas por su elevación y sus superficies planas.

El objetivo de medir la elevación de las terrazas marinas es conocer la elevación a la que se ve afectada la zona de Zemmouri.

RESUMEN

Las terrazas marinas son accidentes geológicos compuestos por superficies elevadas y planas y pendientes pronunciadas. La evolución de estas terrazas está influida en gran medida por la deformación tectónica costera activa. Este estudio investiga el levantamiento de las terrazas marinas a lo largo de la costa oriental de Argel y sus implicaciones para la convergencia de las placas africana y europea y las curvas del nivel del mar. El objetivo del estudio de las terrazas marinas en la zona de Zemmouri es comprender mejor la evolución de las costas de la Tierra y cómo han sido modeladas a lo largo del tiempo por procesos naturales como los cambios del nivel del mar, la actividad tectónica, los parámetros geomórficos y la erosión. Las terrazas marinas proporcionan información valiosa sobre la historia de los cambios del nivel del mar y el ritmo de elevación o hundimiento tectónico de las zonas costeras. Para analizar el impacto del nivel del mar en las terrazas marinas se utilizaron fuentes de datos secundarias, como información cualitativa e imágenes de satélite de alta resolución (SRTM 30 m y ALOS 12,5 m). El trabajo de campo realizado con GPS y altímetros en el lugar del terremoto de Mw=6,8 de Zemmouri, ocurrido el 21 de mayo de 2003, reveló la presencia de dos terrazas marinas bien conservadas, que sirven de marcadores importantes para medir la tasa de deslizamiento de la falla a largo plazo. El análisis pone de relieve la importancia de la deformación tectónica costera activa en la configuración de las costas. Esta investigación ofrece nuevas perspectivas sobre los procesos en curso de convergencia de placas y cambio del nivel del mar a lo largo de la costa oriental de Argel, contribuyendo a nuestra comprensión global de la evolución costera y el potencial de riesgo sísmico en la región.

Palabras clave: Terrazas marinas; Tectónica costera activa; Convergencia de placas; Terremoto; Marcadores geomórficos.

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1. Introduction

The geomorphological parameters used to calculate the changes in the earth's properties can be utilized to determine the changes in the coastal areas. The research of Harris *et al.* (2014) has found that the modification of landforms through the time can be retraced using geographical parameters. (Taib *et al.*, 2022). Other controlling factors such as the topography, climate, lithology, etc. could effectively contribute to the process (Hadji *et al.*, 2013; Mouici *et al.*, 2017; Tamani *et al.*, 2019; Anis *et al.*, 2019). This can distribute the geomorphological properties at different levels (Biolchi *et al.*, 2016). On the other hand, other conditions regarding the tectonic deformation, the volume of the plates, modification in the bedding mode, internal structure shifts, and bedrock of relative position could be accountable for the depleting shoreline and the marine terraces (El Mekki *et al.*, 2017; Whitehouse *et al.*, 2019; Hamad *et al.*, 2021). The study further revealed that such sort of conditions can lead to the multidirectional and unidirectional movement of the tectonic plates upon extension and compression.

Bougrine *et al.* (2019) demonstrated that the eastern shoreline implies an East-west strike-strip fault separation. Figueiredo *et al.* (2019) demonstrated that the tectonic deformations held in the eastern area led to a shortening in the platform of Saharan at a wide level. On the other hand, it is essential to quantify the coastal uplift rates in terms of assessing the tectonic dynamics while estimating the seismic hazard. Most of the world's coastline is covered by a sequence of palaeoshorelines resulting due to the interplay among SL variations and tectonic uplift. Paleoshorelines are also considered as the markers of the previous SL position which helps to reflect the climatic and global to regional tectonic process and are often reflected as the marine terrace sequences. It has been reported in the study of Cerrone *et al.* (2021), that marine terraces are relatively horizontal and flat or gently inclined surfaces of marine origin. These are usually bounded inland by a fossil sea cliff or covered by a layer of coastal sediments (Scerri, 2019; Cerrone *et al.*,

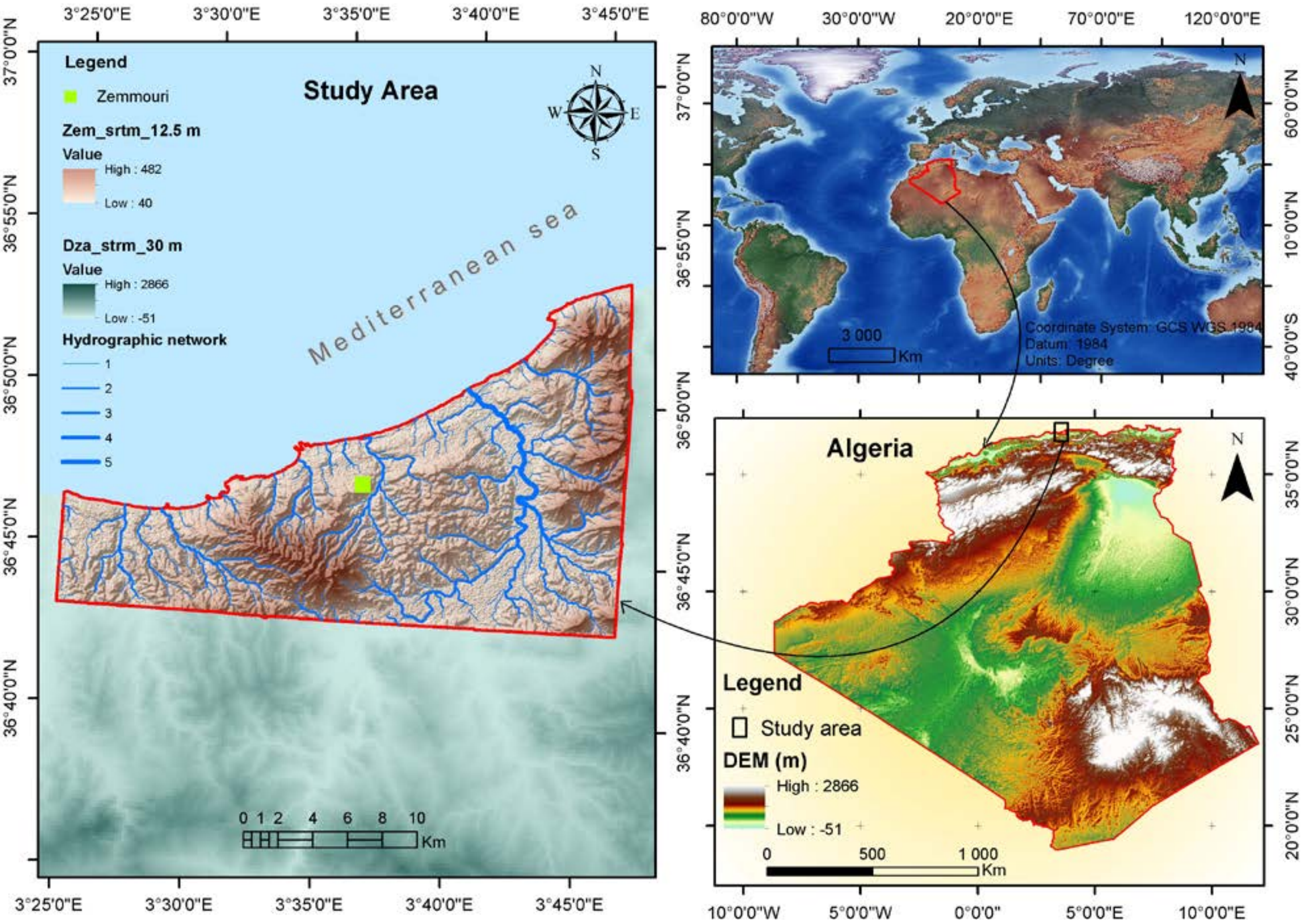

Figure 1. Location of the study area.

Figura 1. Localización de la zona de estudio.

2021). In this manner, the sustained land uplifts upon the SL cycles result in staircase morphologies consisting of a series of marine terraces that are detached by fossil sea cliffs. Shoreline angles which are at the intersection of paleo cliffs and terraces are usually utilised as the geomorphic indicators of the previous SL position while almost time equivalent to interstadial or interglacial SL high stands.

The marine terraces studies usually rely on terrace ages in terms of the constraints of land uplift rates or the relative SL history (Freisleben *et al*., 2021; Muhs *et al*., 2021). As per the study conducted by Normand *et al*. (2019), sea-level curves can have a huge effect on marine terraces.

At multiple scales, the sequence of uplifted marine terraces is extensive and replicate the interaction among the tectonic and climatic process. However, it has been argued in the study of de Gelder *et al*. (2020) that there is a difference in pre and post-MPT morphology which is due to the particular arrangement of components of the sea level. In contrast to this, an easy explanation regarding a first-order morphological difference has been provided by cliff diffusion which is before and after the MPT (Heaton *et al*., 2020). The resulting data obtained in this paper were used for the generation of comprehensive maps and the analysis of geomorphologic and morphometric parameters of the marine terrace as well as the association with the sea level curves in the Zemmouri region located east of Algiers.

2. General setting

The Tell Atlas thrust belt located in Algeria's northern region has a convergence rate of about 4 to 6 mm/year toward Europe (Nocquet and Calais, 2004; Serpelloni *et al*., 2007). Its various folding structures are known to contribute to the active deformation of the coastal zone of Zemmouri (Figure 1). The multiple thrust faults, E-W, and NE-SW trending structures are responsible for the Tell Atlas' significant shortening (Meghraoui and Doumaz, 1996).

Two active structures are located in the Algiers region, which is NE-SW to EW. These structures

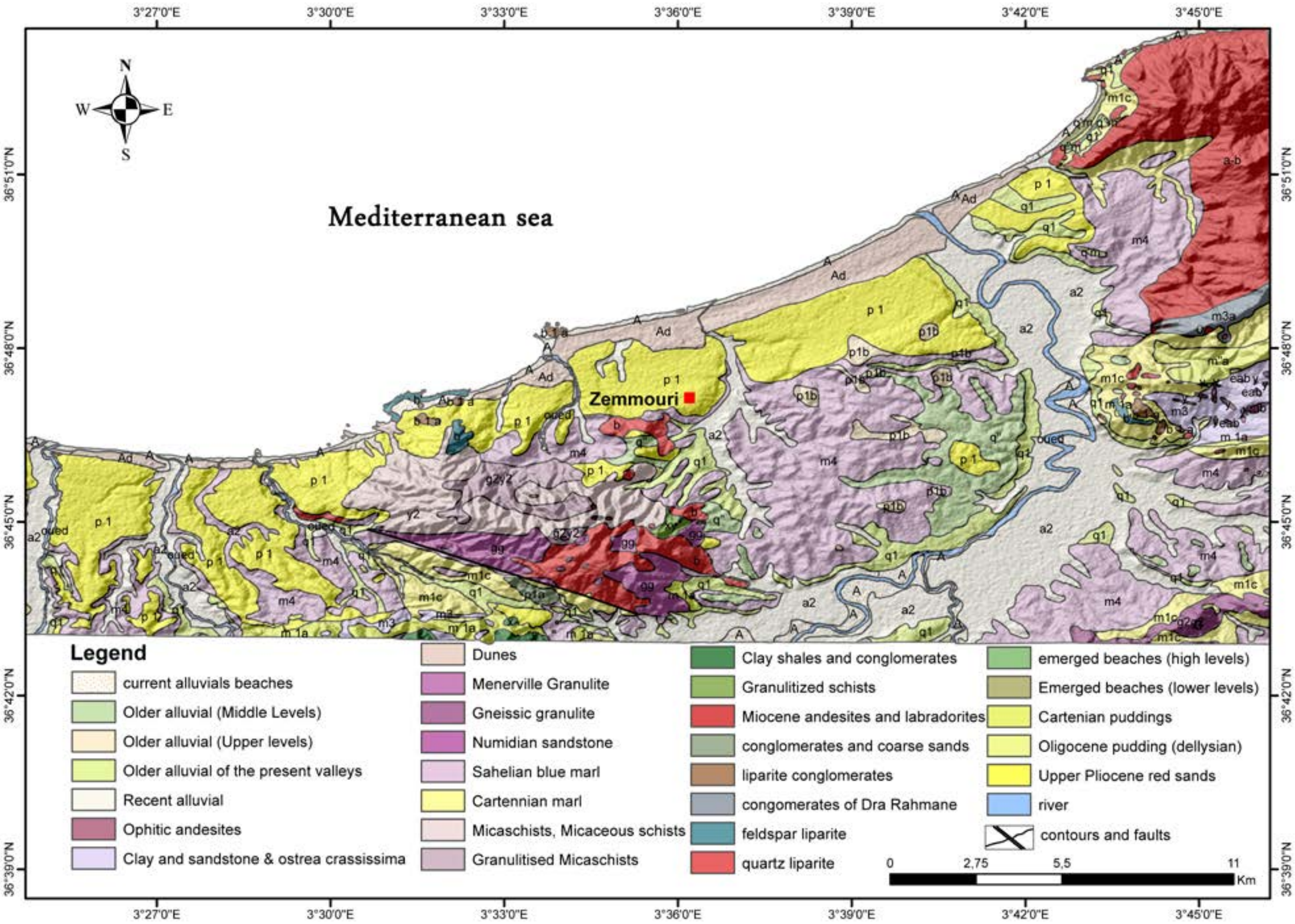

Figure 2. Geological map (with relief, SRTM-12.5 m topographic data) of the Zemmouri region and surroundings.

Figura 2. Mapa geológico (con relieve, datos topográficos SRTM-12,5 m) de la región de Zemmouri y alrededores.

are the southern and northern edges of the Mitidja anticline basin. The height of the region has increased significantly reaching 500 m (Figure 1).

The area under study is mainly composed of basement rocks from the Cenozoic and Paleozoic eras (Figure 2). The structures in this region are overlain by strong overthrust and fold structures (Durand Delga, 1969). The Mitidja basin's active faults are located on the right-stepped and trending faults (Meghraoui, 1988). These structures can extend to the coast and be activated during the 2003 Zemmouri earthquake (Ayadi *et al*., 2008; Belabbes *et al*., 2009; Bounif *et al*., 2004; Meghraoui *et al*., 2004). The northern half of the Zemmouri anticline shows a sequence of late-Pleistocene and Holocene marine terrace units (Meghraoui, 1991) (Figure 2).

According to the seismicity catalog, strong earthquakes have been felt along the northern and southern edges of the Mitida basin (Ambraseys and Vogt, 1988; Benouar, 1994; Harbi *et al*., 2007; Mokrane *et al*., 1994). The most recent earthquakes that have been felt in the Algiers region were mainly caused by reverse tectonics. The most destructive earthquakes that occurred in the region were the powerful earthquakes that occurred in Zemmouri and Tipasa. These two earthquakes are related to the N 45E seismic activities that extend offshore (Ayadi *et al*., 2008; Bounif *et al*., 2003).

3. Material and Method

The data and the method were collected through uplifted terraces and coastal zones which are related to the geomorphology of the Tell Atlas. The morphology of the marine terraces is also linked to various factors such as the sea level, shoreline angle, and cliff and slope index.

The elevation of the Zemmouri area has a significant influence on the scale of marine and alluvial terraces. It has also caused Paleo-wave notches and staircase morphology across these areas (Meghraoui, 2004). For the study of coastal geomorphology, satellite imagery and field investigations were used to characterize the landscape features of the area at a wide level, these include ALOS, SRTM 30 m, and DEM 12.5 m resolution along with the 3-Arc elevation model. These images allowed the study to identify easily the geomorphological markers and provide a potential landscape. The geomorphological markers include the escarpment, shoreline angle, cliff, wave-

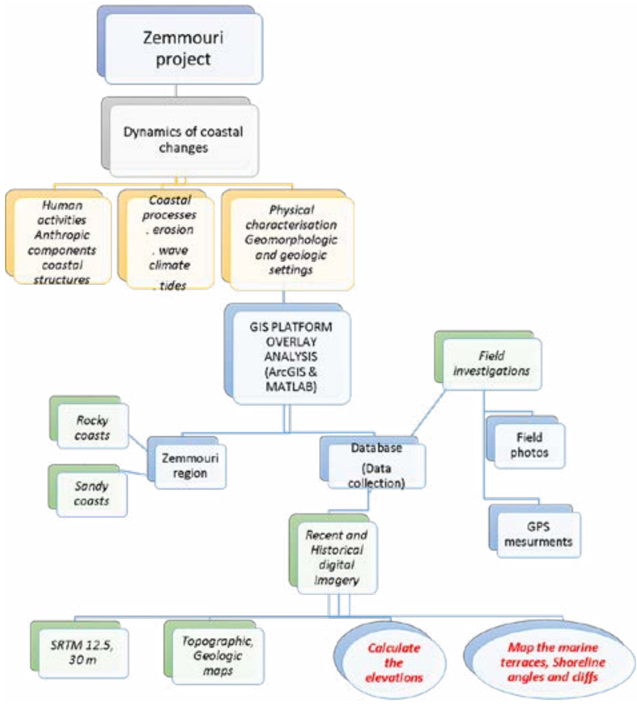

Figure 3. Methodological flowchart of the adopted approach.

Figura 3. Diagrama de flujo metodológico del enfoque adoptado.

cut platform, and marine terraces (Demdoum *et al*., 2015) (Figure 3).

The data collected were processed through tools that are offered by ArcGIS and MATLAB. These tools were used to extract information relevant to hydrographic, topographic, and geomorphological maps. The resulting data were further utilized for the generation of a comprehensive analysis of the morphometric parameters of the marine terrace as well as the association with the sea-level curves in the region of Zemmouri (Figure 3).

The distribution and variation of the data were focused on the coastal and marine terraces. The quantitative geomorphological approach for marine terraces is based on the use of elevation data, GPS, and geographical coordinates (Figure 3).

4. Results

4.1. Evaluation of influence on marine terraces by the erosive action of waves, with the impact of rising sea levels.

The erosive action of waves and rising sea levels both have an impact on marine terraces. Waves can erode the lower parts of marine terraces and modify their shape over time. Rising sea levels can also cover up parts of the terraces, leading to their eventual submergence. However,

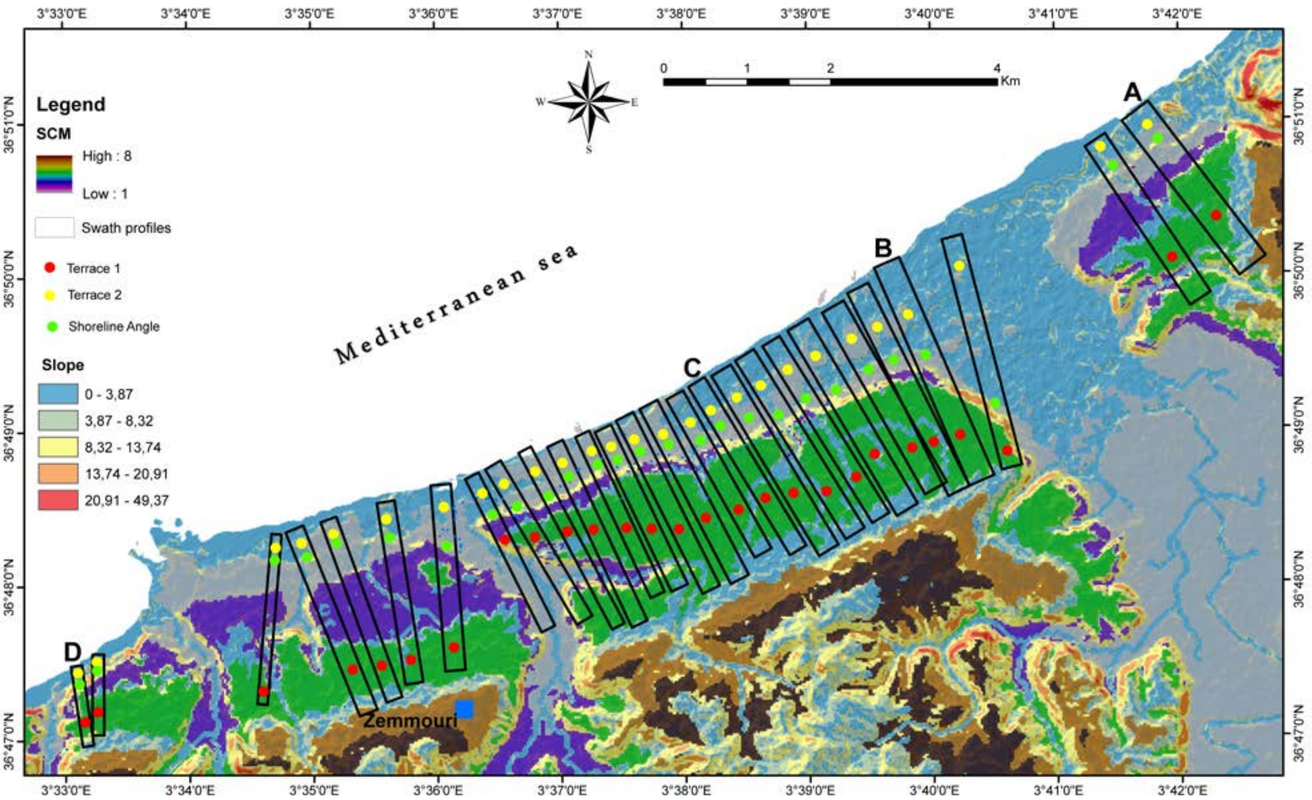

Figure 4. The surface classification model shows Terrace 1, Terrace 2, and shoreline angles in the Zemmouri region.

Figura 4. El modelo de clasificación de superficies muestra la Terraza 1, la Terraza 2 y los ángulos de la línea de costa en la región de Zemmouri.

the primary formation mechanism of marine terraces is still tectonic uplift.

Uplifted marine terraces are caused by tectonic activity along coastlines, specifically the uplift of the Earth's crust due to earthquakes, volcanic activity, or the movement of tectonic plates resulting in the exposure of former sea level surfaces (Saillard *et al.*, 2011). The marine terraces are perceived as natural structures which are developed as the outcome of marine denudation and abrasion (Thompson and Creveling, 2021). These include flat surfaces with their elevation (Table 1) having a steep slope on one side known as ascending and a bit steeper slope on the other side regarded as descending slope (Bilbao-Lasa *et al.*, 2020). These natural marine terraces and the shoreline structure over the shore of Eastern Algiers are generally characterised by their steep and tall characteristics (Figure 4 and Table 1).

Gelder *et al.* (2020) asserted that marine terraces are widely influenced by decreasing and increasing sea levels. Wave dissipation and erosion are the general characteristics of the sea-level curves which can impact the marine terraces (Matsumoto *et al.*, 2021). The destructive waves and the strong wind with marine terraces can act as the genesis for the establishment of rocky shore platforms (Chen *et al.*, 2020). On the other hand, the distinction between vertical and horizontal erosion is important in the formation of marine terraces because it helps to determine the shape and elevation of the terrace relative to the current sea level. (de Gelder *et al.*, 2020). Although the spatial patterns related to the energy dissipation are affected by the water depth. The rate of erosion increases exponentially as the water depth decreases (Authemayou *et al.*, 2017).

Regarding the erosive action of waves over the marine terraces that are located across Algiers, it has been noted that there have been significant changes held over time (Figure 4). On the other hand, the research of Maouche *et al.* (2011) has determined the notions about coastal thrusting and its implication for marine terraces in depth. The research findings demonstrated that in Algiers the marine terraces have seen notable coastal uplifts, particularly after the earthquakes which were held in the Zemmouri in 2003. For instance, in 2003, the earthquake in the eastern region has been reported as Mw= 6.8 (Table 1). Whereas, the notches have appeared over the marine terraces even before and after the Holo-

FID	Lon ° E	Lat ° N	T1 elevation (m)
1	3,705012	36,83941	43
2	3,699056	36,83498	38,57876
3	3,676733	36,81414	38,24461
4	3,670407	36,8159	40,05224
5	3,666842	36,81515	40
6	3,663938	36,81451	40,82337
7	3,658891	36,81387	36,3007
8	3,656403	36,8114	40,45546
9	3,652374	36,80987	40,32255
10	3,647947	36,80971	38
11	3,644176	36,80919	39,19782
12	3,640561	36,80795	38,15869
13	3,636159	36,80706	39,7467
14	3,632507	36,80588	42,8378
15	3,628854	36,80593	41
16	3,625472	36,80606	37,23874
17	3,621041	36,8059	34,73498
18	3,617548	36,8057	35,6847
19	3,61315	36,80512	35,85353
20	3,609115	36,80487	30,71414
21	3,602196	36,79324	40,53839
22	3,596397	36,79194	41,79302
23	3,59248	36,79132	39,98565
24	3,588573	36,79091	38,07226
25	3,576562	36,78861	37,82665
26	3,554356	36,78647	38,12854
27	3,552607	36,78537	35,13005

FID	Lon ° E	Lat ° N	T2 elevation (m)
1	3,695839	36,8493	3,358069
2	3,689529	36,84696	3,08913
3	3,670438	36,83413	1,191437
4	3,663512	36,82893	3,005779
5	3,659368	36,82758	4,840551
6	3,655907	36,82634	6,979505
7	3,651048	36,8245	4,886707
8	3,647273	36,82304	3,308703
9	3,643623	36,82134	1
10	3,640419	36,82008	4,002098
11	3,636919	36,8187	3,267466
12	3,634172	36,81741	2,747785
13	3,630487	36,81614	6,541472
14	3,626593	36,8156	2
15	3,623486	36,81485	3
16	3,620859	36,81438	8,108419
17	3,616929	36,81312	7,817922
18	3,613248	36,81222	7,92598
19	3,609046	36,81089	3,078633
20	3,606138	36,80988	4
21	3,60095	36,80843	2,878481
22	3,593207	36,80715	3,999215
23	3,586096	36,80557	4,147634
24	3,581787	36,8046	6
25	3,578313	36,80414	3,043665
26	3,554183	36,79189	1,251095
27	3,551658	36,7907	3,000382

FID	Lon ° E	Lat ° N	ShA elevation (m)
1	3,697225	36,84781	5,833403
2	3,691164	36,8449	6,739986
3	3,675148	36,8193	3,242377
4	3,665821	36,82457	5,016499
5	3,661515	36,82401	6,349187
6	3,658176	36,823	3,067195
7	3,653759	36,82083	7,456726
8	3,649696	36,81995	5,161769
9	3,646054	36,81815	10,026733
10	3,642019	36,81788	8,608517
11	3,638193	36,81703	6
12	3,635509	36,81543	9,74859
13	3,631188	36,81502	9,703542
14	3,62738	36,81431	9,540586
15	3,62435	36,81342	8,574905
16	3,621677	36,8129	5,024647
17	3,617774	36,81164	5,512399
18	3,615019	36,80953	10,339607
19	3,610789	36,80844	11,400224
20	3,60752	36,80755	9,181897
21	3,601297	36,8042	11,259814
22	3,593624	36,80516	0,989499
23	3,58653	36,8046	7,224016
24	3,582527	36,80311	5,406833
25	3,578158	36,80276	5,168845
26	3,55423	36,79094	5,900994
27	3,551879	36,78946	8,580495

Table 1. Geographical coordinates and elevations of T1, T2, and shoreline angles obtained from fieldwork.

Tabla 1. Coordenadas geográficas y elevaciones de los ángulos T1, T2 y línea de costas obtenidas a partir del trabajo de campo.

cene era (Maouche *et al.*, 2011). Thus, considering the different elements and characterization of the marine terraces across eastern Algiers it can be found that the erosive action of waves has led to different impacts on the geomorphology of the area.

5. Discussion

Marine terraces in the Zemmouri region, are geologically significant features formed by tectonic uplift and marine erosion. They provide evidence of past sea levels and can be used to reconstruct the tectonic and geomorphic evolution of the region.

We have identified two distinct marine terraces in the Zemmouri region, each located at a different elevation above the present sea level. The higher terrace is [43 m], while the lower terrace is [1 m] (Figure 4). These terraces provide evidence of past sea level changes and the tectonic evolution of the region.

Table 1 displays the results from fieldwork conducted at 81 different locations. The geographical coordinates (longitude and latitude) were determined using a GPS device, and the elevations of the locations above sea level were measured using an altimeter.

Our goal was to understand the shape of these marine terraces. We selected four profiles, labeled A, B, C, and D, located perpendicular to the coastline in different areas. We considered the elevations of T1, T2, and ShA. Our study yielded the profiles displayed in (Figure 5), which demonstrate the presence of two flat levels of marine terraces. To determine the difference in the elevation between T1 and T2, we created a diagram based on the elevation of all selected field points, resulting in the representation shown in (Figure 6).

Finally, to validate our findings, we took field photos of the four profiles A, B, C, and D. The results from the field matched our theoretical results, as seen in (Figure 7).

6. Conclusions

Uplifted marine terraces in the Zemmouri region are formed through repeated cycles of active

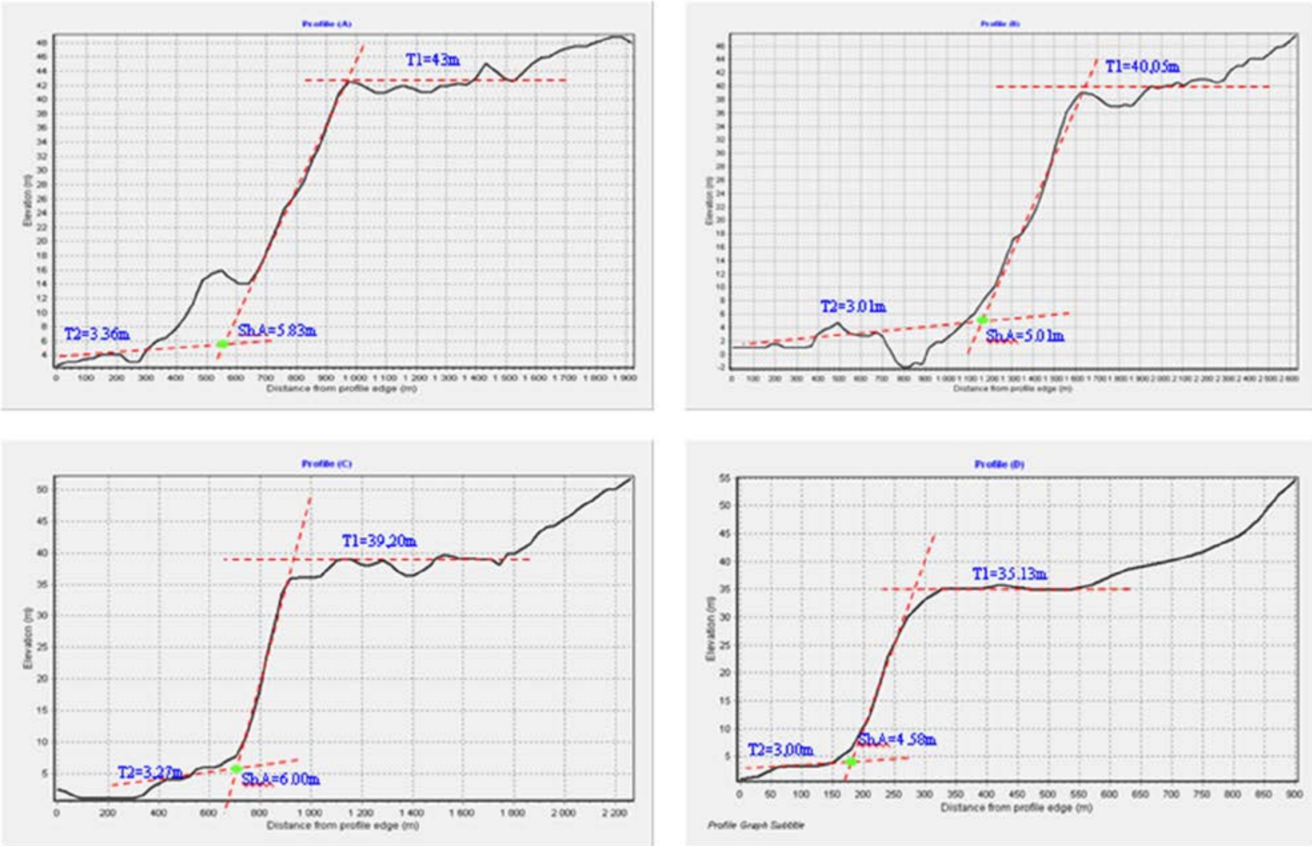

Figure 5. Profiles A, B, C, and D show the difference in elevation between T1 and T2.

Figura 5. Los perfiles A, B, C y D muestran la diferencia de elevación entre T1 y T2.

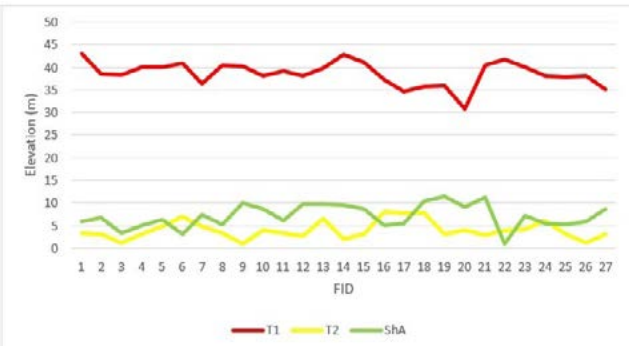

Figure 6. Comparison of elevation between T1, T2, and ShA.

Figura 6. Comparación de la elevación entre T1, T2 y ShA.

tectonic uplift and marine erosion. The process scenario is as follows:

1. Tectonic uplift raises the coast, exposing a flat surface above sea level.
2. Wave action and other erosional processes shape the surface, forming a marine terrace.
3. As uplift continues, the terrace is raised higher above sea level and a new, higher terrace is formed.
4. The process repeats, resulting in the formation of multiple, successively higher marine terraces.

The height of each terrace above sea level reflects the amount of uplift that has occurred, while the shape and profile of the terrace reflect the erosional processes that have taken place.

In this paper, we studied the coastal evolution, distribution, and height of marine terraces in the Zemmouri region which are a result of active coastal tectonic deformation. This deformation is caused by the convergence of the African and European plates, which leads to tectonic uplift and the formation of marine terraces. The study of these terraces provides important information about the tectonic evolution of the region and helps to construct sea-level curves, providing insight into past sea-level changes. The uplifted marine terraces in the area have significant scientific and geohazard implications, and understanding their formation and evolution is crucial for improving our understanding of coastal processes and tectonic activity in the region.

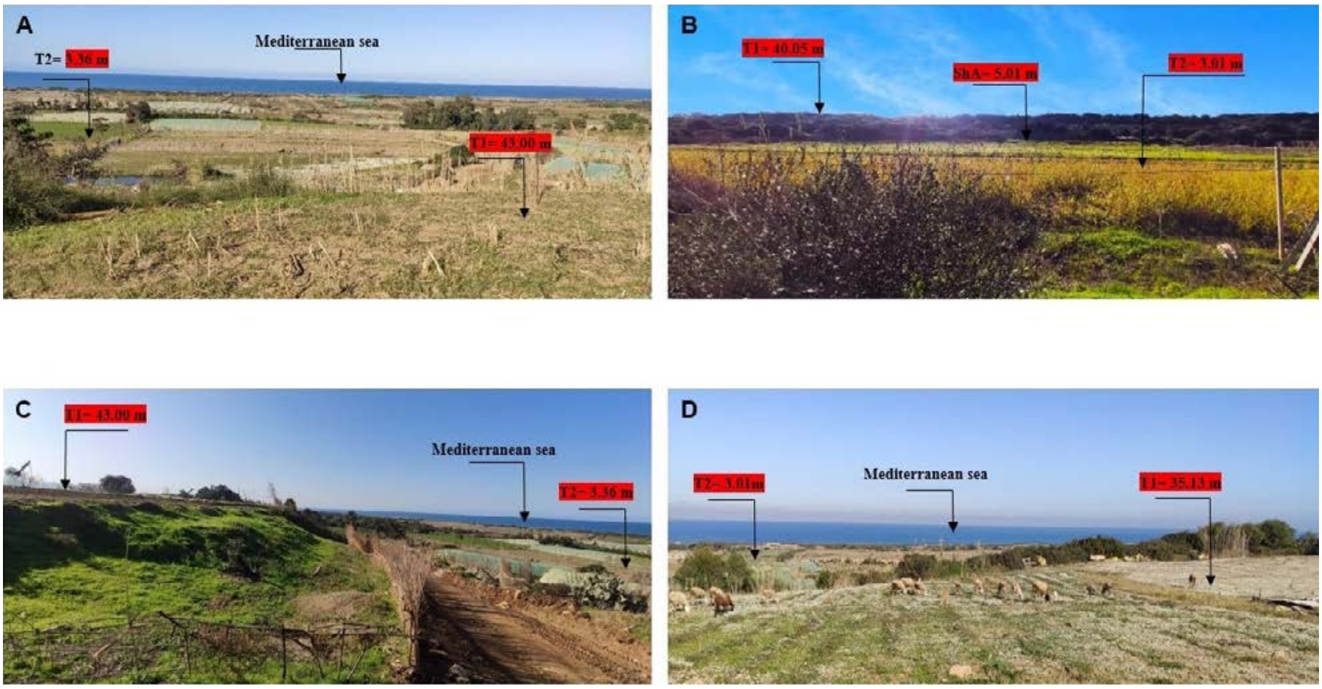

Figure 7. Field photos presented the study area and the four profiles A, B, C, and D formed by T1 and T2.

Figura 7. Fotos de campo que presentan la zona de estudio y los cuatro perfiles A, B, C y D formados por T1 y T2.

This study suggests that the Zemmouri region experienced earthquakes due to plate movement resulting from the convergence of the African and Eurasian continents and the intense tidal movement along its coasts, which affects the deposition and erosion of marine terraces. The similarities in the shape of profiles A, B, C, and D indicate that the sea curves in Zemmouri and east of Algiers were affected by similar factors. Marine terraces are impacted by rising and decreasing sea levels, with rising sea levels potentially submerging them over time. Thus, the study concludes that active coastal tectonic deformation has an impact on marine terraces in the Algiers region.

7. Abbreviations

SRTM - Shuttle Radar Topography Mission; ALOS - Advanced Land Observing Satellite; DEM - Digital Elevation Model; GPS - Global Positioning System; SL - Sea Level; RSL - Relative Sea Level; MIS - Marine Isotopic Stage; T1 - Terrace 1; T2 - Terrace 2; ShA - Shoreline Angle; MPT - Mid-Pleistocene Transition.

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