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A Geomorphological and Environmental Evaluation of Coastal Cliffs Collapse in the Bardai Region, North-eastern Libya

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A B S T R A C T

Due to its carbonate-dominated lithology and exposure to tectonic and marine forces, the Bardai coastal region in eastern Libya is extremely susceptible to cliff collapse. The Bardai cliffs' instability has increased due to micro-fracturing caused by recent seismic activity in the eastern Mediterranean, including moderate to powerful earthquakes in Greece and Turkey. Active retreat, undercutting, and massive rockfalls that endanger human safety and coastal ecosystems were found during field observations Similarly, the region's geological formations, such as Al-Jaghoub, Al-Faydiya, and Al-Abraq, cause the rocks to fracture and fragment due to the pressure of the Al-Jaghoub formation layers on other delicate formations. By creating shockwaves that travel through pre-fractured strata, illicit fishing methods involving underwater explosives beneath rocky cliffs have accelerated structural weakening in addition to natural forces. In order to reduce future risks in the Bardai area, it is imperative to assess coastal hazards and implement sustainable management strategies in light of the combined natural and human pressures.

1 Introduction

A major geological and environmental problem that impacts many coastal areas globally is the coastal cliff collapse. These landforms are especially susceptible to both abrupt and gradual failure because they are constantly changing due to atmospheric and marine forces and Coastal cliff collapses can directly endanger human safety, endanger local infrastructure, and cause serious ecological degradation (Emery & Kuhn, 1982). Large rock masses can suddenly separate, causing devastating effects on settlements (Westoby et al., 2020). Because frequent collapses contribute substantial sediment loads and related contaminants to the nearshore zone, which may deteriorate water quality and disturb delicate marine habitats, the environmental effects go beyond the immediate physical harm (Bełdowska et al., 2022). Cliff erosion and collapse are especially prominent in arid regions such as Libya, where sparse vegetation and fragile carbonate rock formations prevail Coastal rockfall is a persistent hazard along many rocky shorelines, where the gradual retreat and abrupt collapse of coastal cliffs are caused by the combination of marine processes, structural weaknesses, and ongoing weathering According to Queiroz and Marques (2019), anthropogenic pressure has also exacerbated these risks because growing construction and tourism activities are occupying high-risk coastal areas that are already undergoing accelerated erosion due to rising sea levels and increased storm activity. Thus, hazard mapping, sustainable land use planning, and the creation of monitoring techniques that can lower community risks while maintaining the natural dynamics of coastal landscapes depend on an understanding of the mechanisms, rates, and spatial patterns of coastal cliff instability (Imam et al., 2023). Libya's eastern coastline has experienced increasing geomorphological changes in recent decades due to land use, inadequate coastal management, and natural elements like wave attack, salt weathering, and tectonic influences (Lee, 2008). The elevated coastal plain that borders Tobruk City is an emergent portion of the continental shelf. These regions have rocky, narrow, and undeveloped beaches. The coast of Tobruk is largely dominated by a rough topography, with erosional terraces backing the shoreline. (Masoud, 2020). There is still a glaring lack of thorough comparative studies looking at the

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sediment and clay mineral characteristics of neighbouring sabkha systems in eastern Libya, particularly between Wadi Elsahal and Wadi ElSuwani (Masoud et al. 2025). All researchers agree that the findings offer crucial insights into differentiating stable from dynamic sabkha environments and contribute to sedimentology geomorphological mapping and environmental planning in arid coastal regions. The Al Abraq Al Faidiyah and Al Jaghbub formations, which are mostly composed of calcite with trace amounts of quartz and sporadic halite, make up the region's rock cliffs. The carbonate composition typical of these geological units, which are known to contain limestone rich in fossils, is reflected in the high concentration of calcite. Masoud and Khameiss (2024). Coastal cliffs are examples of dynamic geomorphological systems where the environment is constantly changing due to atmospheric and marine processes. Significant environmental and socioeconomic effects, such as shoreline retreat, habitat disruption, and increased sediment loads in nearshore ecosystems, can result from rockfall events along these cliffs (Limber et al., 2021). Wave energy, weathering cycles, and sea level rise frequently exacerbate these instabilities by hastening material detachment and downslope movement (Brain et al., 2023). Therefore, forecasting future coastal change requires an understanding of the mechanisms and effects of cliff-rockfall. The protection of vulnerable communities and efficient management of coastal hazards are further supported by this knowledge. Significant information about the depositional environments, diagenetic processes, and mineralogical composition of the Al Gaghbub, Al Faidiyah, and Al Abraq Formations is revealed by the mineralogical and microfacies analysis of the rock samples under study. With traces of evaporite and detrital minerals like halite, quartz, and kaolinite, the mineralogical composition shows a predominance of carbonate minerals, especially calcite and dolomite. Masoud and Khameiss (2025).

This study's main goal is to pinpoint the precise locations where rockfalls occur along coastal cliffs. Additionally, it looks at the underlying geomorphological and environmental causes of these failures and evaluates the consequences. This work is a first step towards more thorough research in the future with the goal of creating efficient mitigation and management plans.

2 Geology of the region

2.1 The Al Abraq Formation

With a thickness of about 36 meters, the Al Abraq Formation (Lower Oligocene) is a known lithostratigraphic unit in the Tobruk region. It is situated in Cyrenaica, four kilometres north of the town of Al Abraq (Banerjee, 1980). The formation is made up of interbedded dolomitic limestone, dolomite, marl, and calcarenitic limestone. West of Wadi al Kuf, there are notable slump structures and distorted bedding that show lithological variability brought on by Oligocene–Miocene sea-level fluctuations (Banerjee, 1980). The base of the Al Abraq Formation in Cyrenaica is composed of glauconitic clayey siltstone, marly deposits, and nummulitic limestone intercalated with algal limestone (Abdulsamad et al., 2009). Furthermore, in the Tobruk region, rocks formerly categorised as the Al Khowaymat Formation are now identified as belonging to the Al Abraq and Darnah Formations, whereas in Al Burdi, these rocks correlate with the Cretaceous Chalk and Al Abraq Formation (Megerisi & Mamgain, 1980).

2.2 The Al Faidiyah Formation

The oldest exposed Miocene rock unit in the Tobruk region is the Al Faidiyah Formation (Upper Oligocene–Lower Miocene). Fossiliferous clay beds, marly limestone, and thick to thin limestone beds characterise its lithology. A shallow marine depositional environment is reflected in this unit's varied collection of fossils, which includes serpulid worm tubes, echinoids, oysters, Operculina complanata, and Lepidocyclina species (El Deftar & Issawi, 1977). The earlier identification of Nummulites fichtelli within the formation was later revised by El Hawat and Shelmani (1993). Pietersz (1968) coined the term "Al Faidiyah Formation" to refer to the calcareous rocks and shale that cover the Shahat Formation, highlighting its stratigraphic significance in tracking the change from Oligocene to Miocene marine environments.

2.3 The Al Jaghbub Formation

The most extensively distributed formation in the Tobruk region is the Al Jaghbub Formation (Early-Middle Miocene), which has a maximum thickness of 34.5 meters (Adam, 2018). It is well-exposed in many locations, particularly in abdominal areas, and is made of firm limestone that ranges from yellowish-white to reddish (Fig. 1). This unit's widespread distribution is indicative of shallow marine depositional conditions linked to reef-building environments in the Early to Middle Miocene. Understanding the palaeoecology of Miocene coral reefs and the development of Mediterranean-Tethys palaeogeography depends heavily on the Al Jaghbub Formation (Khameiss et al., 2024). It is an important reference point for geological mapping and stratigraphic correlation along the eastern Libyan coast due to its wide exposure and lithological features.

Figure1. The different formations in the study area**.**

3 Study Area:

The study area is situated in north eastern Libya, roughly 25 kilometers west of the Egyptian border and 120 kilometers east of Tobruk. Because of its vast expiation of coastal cliffs and the wide exposure of many geological formations that offer important opportunities for geomorphological study, This area part of one of Libya's most important geological zones. Along with this area Wadi El-Suwani, Wadi Rezeq, Wadi El-Rahib and Wadi El-Gattara, are among the significant coastal valleys and picturesque shoreline landscapes found there Fig2.

Figure 2. shows the area of study.

4 Materials and Methods

Between March and June 2024, several visits were made to conduct fieldwork.

The following were involved in data collection:

Measurements and inspections at the ground level using portable GPS devices.

High-quality photographic records taken from a small fishing vessel and the land.

Visual evaluation of fracture zones, joint patterns, and lithological characteristics.

Compilation of anecdotal evidence and observations from locals and fishermen.

The documentation concentrated on finding evidence of recent collapses, active erosion, and weathering characteristics like cracks, overhangs, and notches (Young & Ashford, 2006).

5 Results &Discussion

The geological formations in the area, particularly the Al-Faidiya Formation, exhibit relatively weak and unstable characteristics compared with the surrounding units. This formation contains clay that is highly susceptible to slipping, rapid disintegration, and structural weakening, which increases its vulnerability to fracturing and rockfall. Fault development within these materials further enhances the likelihood of cracking and collapse, while seismic activity acts only as a secondary contributing factor to these in From Figure 3 to Figure 11 illustrates the rockfall occurrences in the area stabilities.

The research results demonstrate the ongoing retreat of the Bardai cliffs, with undercut notches, overhangs, and abrupt block failures caused by weathering and wave erosion. Even though they were offshore, earthquakes that were recorded in the eastern Mediterranean in 2025 caused enough ground motion to worsen already-existing fractures in the Bardai limestone. The buildup of new rock fragments at the base of the cliff after seismic swarms supports the link between seismic shaking and cliff instability.

Additionally, the coastal system has become even more unstable due to destructive fishing methods like using dynamite beneath cliff overhangs. In order to accelerate rock detachment and increase the frequency of collapses, explosions produce artificial seismic waves that reverberate within pre-existing cracks. In addition to directly endangering fishermen, these activities worsen geomorphological degradation and harm marine habitats. A multifaceted cause of cliff collapse in Bardai is demonstrated by the combined effects of tectonic activity and human-induced vibrations, underscoring the critical need for coastal monitoring, enforcement against illegal fishing, and the creation of community-based risk awareness initiatives.

Mechanical wave erosion and subaerial weathering appear to be the main causes of cliff collapse in Bardai. Pre-existing joints and fractures that permit water penetration weaken the limestone layers, despite their relative resistance. Rock disintegration is further aided by salt crystallisation and wind action. The steep inclination and lack of vegetation cover also make mass wasting more likely. The absence of monitoring or preventative measures in the region exacerbates these natural factors.

Table 1 lists the earthquakes that happened in the Mediterranean Sea this year across from the Libyan coast.

Location	Magnitude (Mw)	Date	Time (UTC)	Impact	Source
Santorini–Amorgos, Greece	Mw 5.2	2025-02-05	19:09	rockfalls, seismic swarms, and preemptive evacuations.	Triantafyllou et al. 2025, Geosciences
Santorini–Amorgos, Greece	Mw 5.2	2025-02-10	20:16	Slope failures and foreshock-aftershock.	Triantafyllou et al. 2025, Geosciences
Sea of Marmara, Türkiye	Mw 6.2	2025-04-23	09:49	359 injuries, a single death, and moderate damage.	Korkusuz Öztürk et al. 2025, JGR Solid Earth
Kasos, Greece	Mw 6.1	2025-05-14	01:51	No casualties were reported in the eastern Mediterranean.	Papadopoulos et al. 2025, Bulletin GSG (preprint); EMSC Special Report
Heraklion, Crete, Greece	Mw 6.0	2025-05-14	Night	wide trembling, a protective reaction.	Papadopoulos et al. 2025, Bulletin GSG (preprint); EMSC Special Report
Rhodes region, SW Turkey	Mw 5.8	2025-06-03	23:17	About 70 people were hurt, and one person died from panic.	Özdemir & Cakti 2025, Soil Dyn. EQ Eng. (in press); Kandilli Obs. Report
Balıkesir (Sındırgı), Türkiye	Mw 6.1	2025-08-10	16:53	There was one death, more than fifty injuries, and building damage.	Utkucu et al. 2025, Tectonophysics (preprint).
Kefalonia, Ionian Sea, Greece	Mw 4.0	2024-03-04	07:06	Damage-free swarm offshore Myrtos Gulf.	Anagnostou et al. 2025, Pure Appl. Geophysics
Kefalonia, Ionian Sea, Greece	Mw 3.9	2024-03-04	17:11	Swarm-like activity no effects.	Anagnostou et al. 2025, Pure Appl. Geophysics
Euboea region, Greece	Mw ~4.5	2025-05-18	—	Over fifty structures were damaged by the swarm.	Chatzipetros & Pavlides 2025, Annals of Geophysics (in press); NOA Bulletin

There are various signs of active retreat on the cliffs in Bardai. Key conclusions include:

extensive undercutting at the base of the cliff as a result of ongoing wave action.

Overhang formation is followed by abrupt block failures.

There are several meters of inland cracks that point to an impending collapse.

Large rock fragments build up at the base, creating transient talus slopes.

Cliffs facing the wind had more severe erosion, especially after storms. Over the course of three months, significant variations in cliff position and shape were captured in field photos.

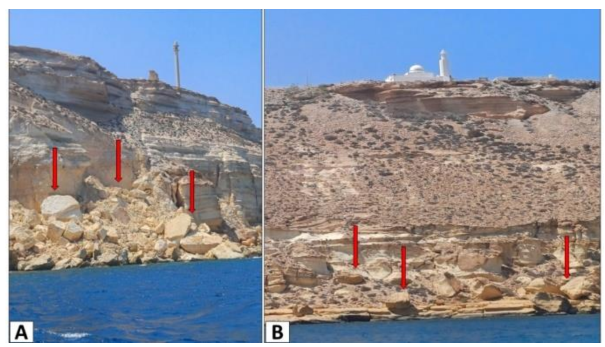

Figure 3. A and B illustrates rock masses from the high coastal cliffs have recently collapsed and moved downward into the sea.

Figure 4. depicts the marine terrace with a stack of fallen rocks.

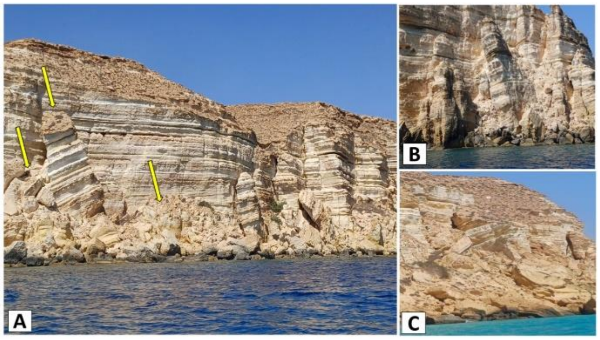

Figure 5. A, B and D represents forms of chemical weathering rock dissolution and the development of rock pillars.

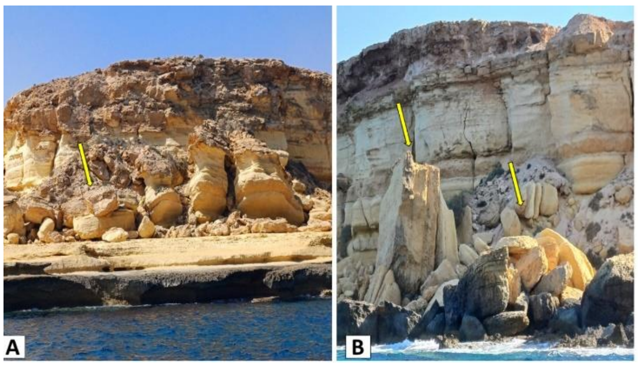

Figure 6. A, B shows the collapse of rock masses from the Fadiyah Formation onto the terrace representing the Al-Abruq Formation.

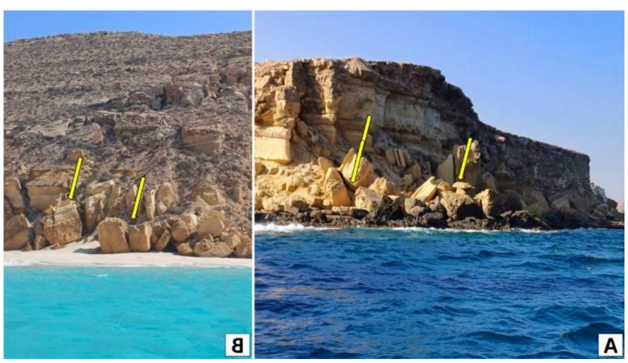

Figure 7. A shows the collapse of large rock blocks and B shows the large fallen rocks resting on the beach sands obstructing the area

Figure 8. shows the downslope movement of rocks from the Jaghbub Formation toward the Fadiyah Formation.

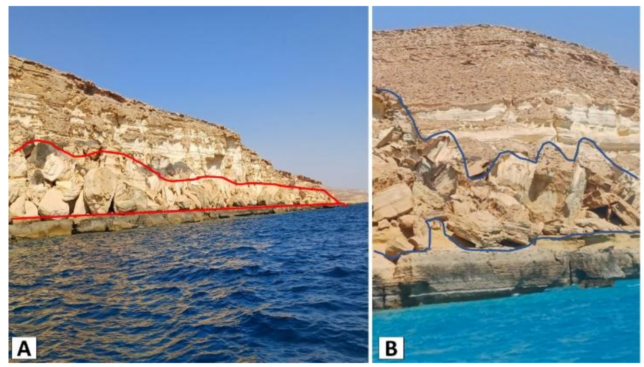

Figure 9. A and B shows rock collapse and dissolution caused by wave action and chemical weathering.

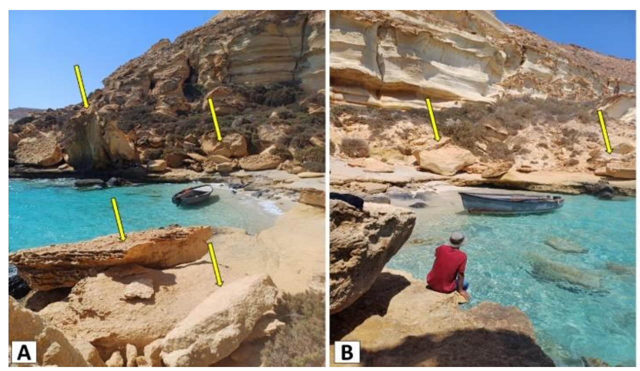

Figure 10. A and B shows the accumulation and collapse of rocks leading to the closure of the shoreline

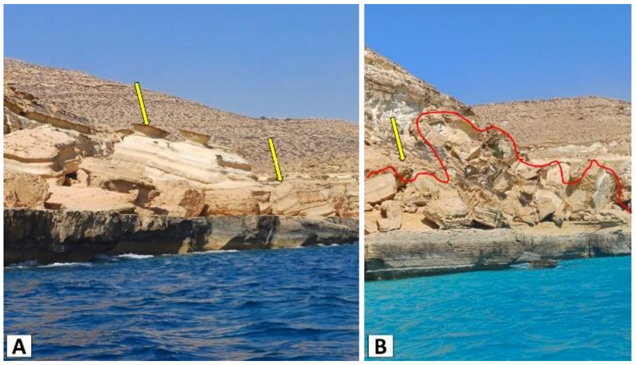

Figure 11. A represents chemical weathering that produced a table and mushroom-shaped form while B shows the accumulation of rocks on the marine terrace

6 Conclusions

The rocky cliffs in the Bardai coastal zone are gradually weakened by severe weathering and erosion processes, which cause frequent rockfalls and the development of serious structural fractures. This instability may be made worse by the regular seismic activity offshore in the Mediterranean, which may cause cliff-side rock masses to shift and loosen. Furthermore, it has been documented that uncontrolled and destructive harvesting methods that target marine organisms disrupt the integrity of nearshore rock platforms, increasing cliff instability and hastening the degradation of the marine and coastal environments.

7 Recommendations

Create a monitoring program with GPS mapping and drones.

Restrict public access and construction near the edges of unstable cliffs.

Encourage public awareness initiatives in coastal communities.

Promote more geotechnical and geological research.

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