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Coastal inundation deposit in the fluvial plain of Oued Mlaleh (Tangier Bay, Morocco)

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Abstract. When it comes to natural disasters, tsunamis stand out for their destructive nature, leaving their mark on landscapes and human history. The tsunami of 1755 BCE is a major historical event that struck the countries around the Gulf of Cadix, inflicting significant damage to infrastructure and resulting in substantial human casualties. This study investigates a coastal inundation deposit located in the fluvial plain of Oued Mlaleh (Tangier Bay, northern Morocco). The Holocene sequence is studied using a multiproxy approach, involving sedimentological, morphoscopic, and micropaleontological analyses. These analyses collectively provide strong evidence of a high-energy event.

Keywords: Sedimentology; Micropaleontology; High-energy event; Tangier Bay; Morocco

1 Introduction

In recent years, extreme weather events have become increasingly frequent. Because of the frequency and urgency of these events, the study of high-energy phenomena and their impact on coastal systems, as well as efforts to reconstruct, understand and quantify past events, have received considerable attention from the scientific community.

High-energy events, such as tsunamis and storms, can have devastating effects on human settlements and natural coastal ecosystems [1,2].

Morocco, which is located in a vulnerable region, faces the threat of natural hazards such as earthquakes, tsunamis, and storms. However, these events have been little studied at regional level.

Recent studies have begun to shed light on this issue, revealing the presence of high-energy deposits along Morocco's Atlantic coastline [3–6], and others.

This study analyses a high-energy deposit in a Holocene outcrop located in Tangier Bay, 500 m from the seashore, on the banks of the Oued Mlaleh, giving an overview of their sedimentological and micropaleontological characteristics.

2 Study Area

The study area is situated within the Bay of Tangier (Fig. 1a), along the bank of the Oued Mlaleh, approximately 500 meters from the beach. It is bounded by the port to the West and Cap Malabata to the East (Fig. 1b). This bay exhibits a dual coastal typology, with a western coastline characterized by a sandy beach extending

approximately 4.8 km, while the eastern coast is marked by rugged terrain.



Fig. 1. Location of the studied area. (a) Location of Tangier in the Strait of Gibraltar; (b) Overview of Tangier coast.

The primary rivers flowing into the bay include the Mlaleh, and Mghogha. These watercourses

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predominantly transport silt and fine sand, except for the Halou Oued, which conveys pebbles, gravel, and sand.

The coastal area exhibits varying substrates, with sandy foreshores transitioning to pebbles further eastward from the Mghogha Oued to the Borj region. This rocky coastline spans approximately 3.6 km from Ghandouri Fort to Malabata Cap (Fig. 2), interspersed with intermittent sandy beaches, including the 0.5 km-long Borj beach which is the largest one.

From a geological perspective, the Bay of Tangier exhibits three distinct geological units [7]. These units are as follows (Fig. 2):

1. The Fahs hilly plain, primarily comprised of Cretaceous clays and marls, constitutes the Tangier external unit.
2. The Marchan massif, characterized by the presence of Melloussa pelites, is overlain by Aquitanian Nummidian sandstones.
3. The Anjra massif, composed of Beni-Ider flyschs, features facies consisting of red limestone marls followed by micaceous sandstone marls.

The primary source of sand replenishing the bay stems from the erosion of the Marchan and Anjra massifs due to coastal processes [7].

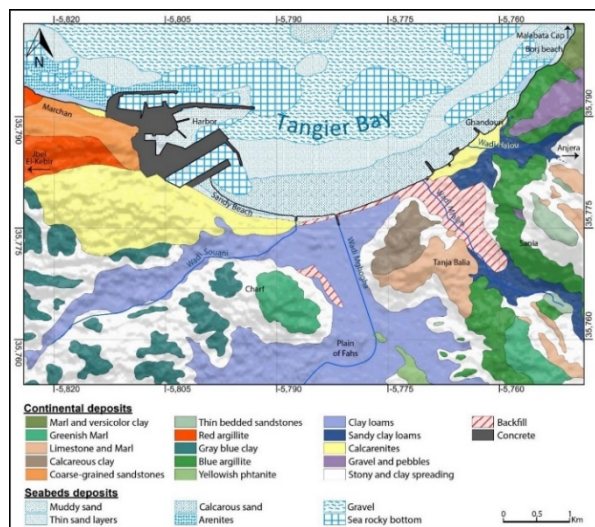


Fig. 2. Geological map of Tangier Bay (after [8]).

3 Methodology

3.1 Field work

In Mai 2023, two field missions in the bay of Tangier to collected sediment samples from the Holocene Oued Mlaleh outcrop. The samples were selected to designate different units from the outcrop, namely TA2 (1), TA2 (2), TA2 (3), and TA2 (4). These samples were intended for subsequent grain size analysis, morphoscopic analysis, and micropaleontological examination. The field study encompassed a comprehensive assessment, involving the morphological characterization, stratigraphic establishment, and lithological identification of the deposits. It should be noted that the outcrop studied lies some 500 meters inland from the coastline.

3.2 Grain size

Sieve analysis was conducted to characterize sediment by determining the size distribution of its constituent grains. In the laboratory, the four samples underwent a dry-sieving procedure following established protocols [9]. After thoroughly washing them and separating the sand fraction, the samples were treated with HCl and H₂O₂, then dried in an oven set at 80 °C. A column with twelve vibrating screens was used for the dry-sieving procedure in accordance with AFNOR guidelines. Each sieve's leftover material that was kept was weighed exactly. The Gradistat software [10] was used to derive crucial metrics such as means, skewness, and sorting.

3.3 Morphoscopic

Morphoscopic analysis was conducted using a binocular loupe, which served as the main observational tool in each sample where the 500 µm fraction was used [11]. The primary objective of this step was to categorize the general shape of the quartz grains, in order to determine whether they are rounded, angular, sub-rounded or sub-angular. The examination included close inspection of the surface texture of the quartz grains [12]. This determined whether the grains exhibited characteristics such as abrasion or other textural attributes.

3.4 Micropaleontology

Microfossils are extracted from the samples using binocular loupe. Then, taxa are named and enumerated. The identification process in a typical microfossil study will follow the guidelines outlined by [13,14].

4 Results

4.1 Lithostratigraphic and grain size analysis

4.1.1 Lithostratigraphic analysis

Within the stratigraphic section under study, six unique stratigraphic units have been found: Gray clays create a layer that is about 60 cm thick at the base of the section, intermingled with bioclasts that are mostly made up of mollusc fragments.

The layer of sandy clays with a brownish color that is just above this one, which serves as the section's base, is about 20 cm deep. It is obvious that the clay contains fine sand. Crabs, which live along the banks of the Oued Mlaleh and can be seen all along the riverside, are a prominent animal bioturbator in this stratum, the sample TA2 (1) was taken from here (Fig. 3).

Following this, a band of coarse sand that is 6 cm thick makes up the section's main layer. Two samples were taken from this layer: TA2 (2) at the base of the layer and TA2 (3) at the top (Fig. 3).

Sandy clays are subsequently observed, along with animal bioturbation of the same origin as observed earlier. The thickness of the layer is approximately 20 cm, and a fourth sample named TA2 (4) was taken.

Fine, brownish sands, about a dozen centimeters thick, overlay the bioturbated sandy clays. No bioturbation or sedimentary structures were observed within this layer.

A layer of contemporary soil with roots and vegetation that is 20 cm deep and of friable consistency covers the section (Fig. 4).

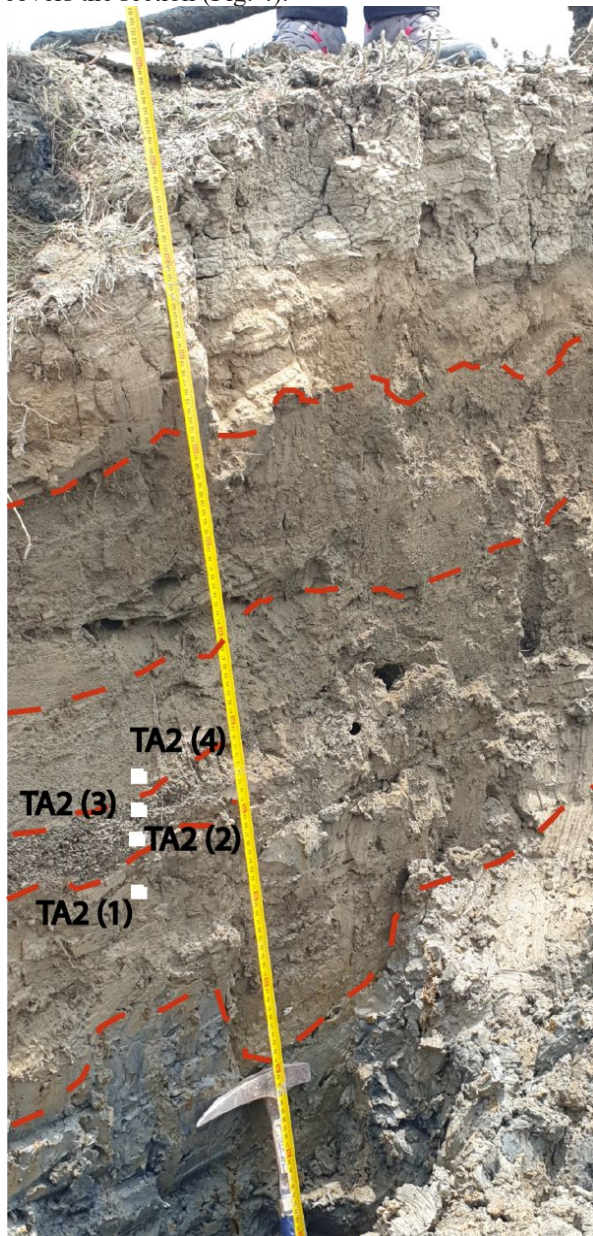


Fig. 3. Photo of section and location of the samples.

4.1.2 Grain size analysis

The deposits TA2 (1) and TA2 (4) are dominated by fine sand, silt, and clay. The deposits TA2 (2) and TA2 (3) shows a very dominant sandy fraction.

The sediments from samples TA2 (1) and TA2 (4) are well sorted, and their skewness coefficient is compatible with a transport linked to a strong current (positive Sk). The sandy samples TA2 (2) and TA2 (3) are poorly to moderately sorted, but while the skewness coefficient of TA2 (2) is also positive, TA2 (3) shows a negative coefficient (Table 1).

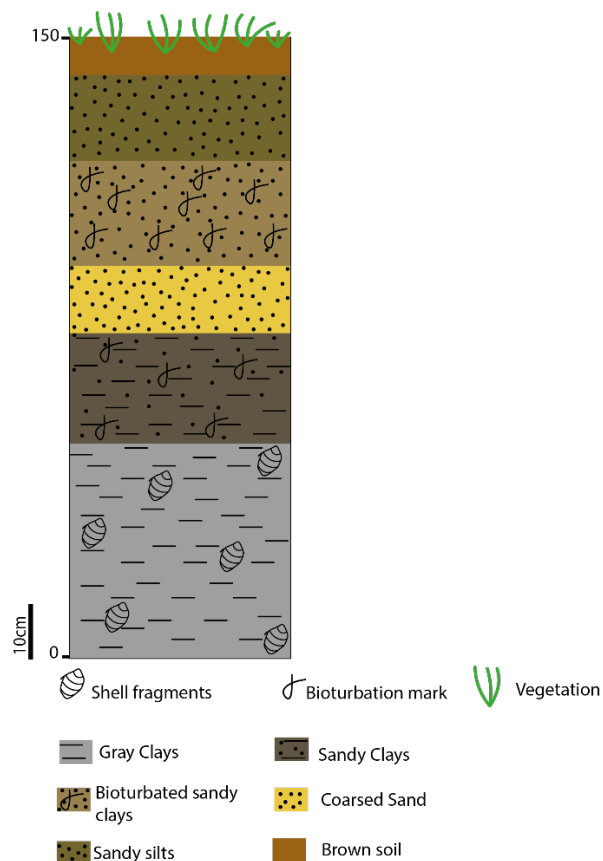


Fig. 4. Stratigraphic log of the studied outcrop.

Table 1. Granulometric parameters.

Samples	Mean (µm)	Kurtosis (µm)	Skewness (µm)	Sorting (µm)
TA2 (1)	58.28	1.082	0.151	1.321
TA2 (2)	432.5	0.762	0.035	2.556
TA2 (3)	825.4	0.613	-0.319	1.937
TA2 (4)	60.32	1.272	0.210	1.395

4.2 Morphoscopic analysis

The morphoscopic examination of quartz grains (Table 2) reveals that Sub-rounded grains have a 67.7% average and Angular grains have a 22% value whilst the average for the Rounded grains is no more than 10.5%.

Table 2. Percentages of angular; sub-rounded; rounded quartz grains in the TA2 samples.

Samples	Angular (%)	Sub-rounded (%)	Rounded (%)
TA2 (1)	18	68	14
TA2 (2)	25	73	2
TA (3)	25	65	10
TA2 (4)	20	64	16
Average	22	67.7	10.5

4.3 Micropaleontological analysis

Micropaleontological analysis of sand samples TA2 (1), TA2 (2), TA2 (3); and TA2 (4) revealed a notable

abundance of microfauna. Figure 5 shows the detailed results.

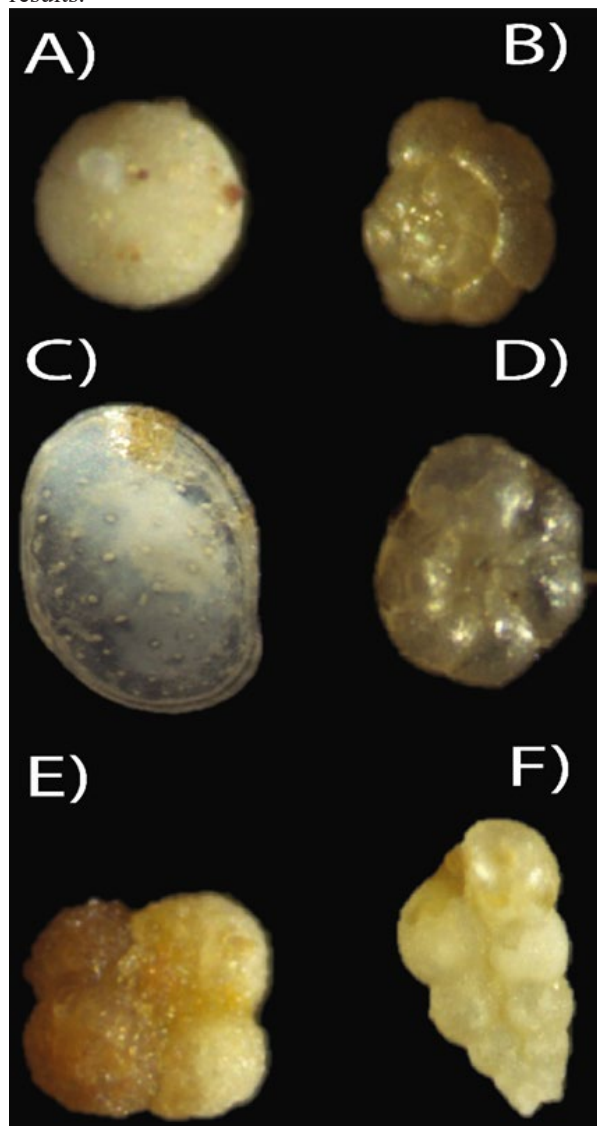


Fig. 5. Photos taken by a microscope; A) *Orbulina universa*; B) *Ammonia sp.*; C) *Ostracod*; D) *Ammonia sp.*; E) *Globigerina sp.*; F) *Bolivina sp.*

The micropaleontological assemblage has a diversified makeup, with foraminifera and ostracods dominating. Benthic foraminifera, particularly *Ammonia sp.*, and *Bolivina sp.* but also a great number of ostracod valves still intact and preserved were found in sample TA2 (1) which is the one directly under the event, but planktonic foraminifera, such as *Orbulina universa*, and *Globigerina sp.*, are present in great numbers in both layers of the event TA2 (2) and TA2 (3) in addition to some benthic foraminifera mentioned above. The last sample just above the event layers presents very scarce microfaunal composition, with very few benthic foraminifera and even fewer planktonic foraminifera. Benthic foraminifera such as, *Ammonia sp.*, *Bolivina sp.*, and planktonic foraminifera such as *Orbulina universa* and *Globigerina sp.*, as well as ostracod valves were meticulously identified in the samples and are visually represented in Figure 5.

5 Discussion

A high-energy deposit generally transports and deposits different fractions: the sandy, silty, and clayey fraction mixed with clasts and bioclasts of allochthonous marine organisms.

In the deposit of the Bay of Tangier, the grains are poorly sorted with a reverse granuloclassification sequence, where at the base we note the presence of sandy clays, followed by the high-energy event layer with poorly sorted and poorly classified coarse sands, covered by a layer of sandy clays on top, as well as the presence of allochthonous marine organisms (bioclasts).

The morphoscopic analysis reveals that the quartz grains have a subrounded and shiny appearance, indicating marine aquatic reworking.

The use of micropaleontology to determine the origin of tsunami deposits is now frequently employed [15,16]. In the high-energy event layer, numerous marine bioclasts have been identified, including shell fragments, bivalves, and gastropods. The foraminifera found in the four layers of the Oued Mlaleh section (TA2 (1), TA2 (2), TA2 (3), and TA2 (4)) are predominantly marine species, represented by *Ammonia sp.*, *Orbulina universa*, *Bolivina sp.*, and *Globigerina sp.* [3,17,18] discovered some of the same specimens found here in their foraminiferal assemblage in sediments from Tahaddart.

The presence of benthic foraminifera in all four of the layers studied was noted, as was their rarity in the TA2 (4) layer, which is the one just above the event layer (the high-energy event layer). The existence of strong hydrodynamic activity and transport processes is illustrated by the presence of broken and poorly preserved tests. Planktonic foraminifera were found only in the event layers and in very limited numbers in the layer just above it. The total absence of ostracods, with the exception of those found in abundance in sample TA2 (1), may indicate that the conditions created by the extreme waves of the event prevented their preservation in the other layers, notably due to the fragility of the ostracod valves.

6 Conclusion

The study of tsunamis remains of paramount importance. These extraordinary natural events, characterized by their immense destructive potential, have far-reaching impacts on coastal communities and environments, and continue to pose a significant threat to this day.

The granulometric study of the samples collected from a deposit near the bank of Oued Mlaleh located in the Bay of Tangier displays both unimodal (TA2 (1), TA2 (3), and TA2 (4)) and bimodal (TA2 (2)) characteristics. The bimodal character suggests that the sediment was subjected to a strong, high-energy regime, and the morphoscopic study suggests that the sediment was subjected to aquatic transport. Likewise, the micropaleontological analysis shows a diversity of benthic, planktonic, and ostracod foraminifera such as *Orbulina universa*, *Globigerina sp.*, *Ammonia sp.*, and *Bolivina sp.*, which means that the deposits originated

from the sea and were deposited by a high-energy event. In perspective, our future investigations will focus on more detailed sedimentological analyses, such as a microtexture study of the quartz grains, a quantitative micropaleontological study and a geochemical study of the major and minor elements.

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