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Neotectonic uplift rates and river incision patterns in the atlas mountain foothills

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Abstract

Roughly 65% of all active mountain belts on Earth show measurable neotectonic deformation, yet foothill zones, the transition between orogen and foreland, remain less documented than their higher-elevation counterparts. This research quantified neotectonic uplift rates and associated river incision patterns across the northern foothills of the Atlas Mountains in Morocco, focusing on four tectonic zones spanning a 280 km transect. Geomorphic indices including the stream-length gradient index (SL), hypsometric integral (HI), valley-floor width-to-height ratio (Vf), and basin asymmetry factor (AF) were computed for 32 catchments using a 12.5 m ALOS PALSAR DEM. Terrace dating relied on optically stimulated luminescence (OSL) ages from 18 alluvial terrace levels, supplemented by radiocarbon dates from six organic-rich fluvial deposits. Results indicated that uplift rates ranged from 0.31 mm/yr in the southern sector to 1.14 mm/yr in the central zone during the Late Pleistocene-Holocene interval. River incision depths correlated positively with SL anomalies ($r = 0.83$, $p < 0.001$) and inversely with Vf values ($r = -0.76$, $p < 0.001$). Catchments draining the central zone returned the highest HI values (0.58-0.71), pointing to a youthful, tectonically rejuvenated landscape. The spatial pattern of uplift mirrors known fault segmentation, with the highest rates coinciding with the Ait Attab and North Atlas fault strands. These geomorphic markers offer an independent check on geodetic velocity fields and can inform seismic hazard models for the densely populated foothill corridor between Beni Mellal and Khouribga.

Keywords: Neotectonic uplift, river incision, Atlas Mountains, tectonic geomorphology, stream-length gradient index, hypsometric integral, alluvial terraces, landscape response, optically stimulated luminescence

Introduction

Between 2005 and 2020, at least 14 moderate earthquakes (Mw 4.0-6.3) struck the Atlas mountain system, reminding geoscientists that the collision zone between the African and Eurasian plates is far from dormant [1]. The Atlas Mountains of Morocco, a 2,500 km-long intracontinental chain, absorbed much of the Cenozoic shortening generated by Africa-Eurasia convergence at roughly 4-5 mm/yr [2]. While the high summits above 3,000 m have attracted detailed structural and thermochronological work, the foothill belt sitting between 400 and 1,200 m elevation has received less attention, despite hosting most of the region's population and agricultural activity.

Foothill zones are geomorphologically sensitive recorders of tectonic forcing. Rivers that drain from high topography onto the foreland adjust their longitudinal profiles to base-level changes imposed by fault displacement. Knickpoints, unpaired terraces, and anomalous steepness indices accumulate along reaches where uplift outpaces fluvial erosion [3]. Interpreting these features quantitatively requires coupling morphometric analysis with absolute dating of abandoned terrace surfaces [4].

The stream-length gradient index, introduced by Hack in 1973, detects variations in channel steepness that may signal differential rock uplift or lithological contrasts [5]. The hypsometric integral summarises the distribution of elevation within a catchment and distinguishes youthful landscapes (HI > 0.5) from mature or peneplained ones (HI < 0.3) [6]. When combined with valley-floor geometry (Vf ratio) and basin asymmetry (AF), these indices form a toolkit that can rank catchments by their relative tectonic activity without expensive instrumentation [7].

Previous work along the Atlas front relied on GPS campaign measurements and scattered

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structural cross-sections [8,9]. A gap persists in spatially continuous uplift-rate estimates anchored to dated geomorphic markers. This research filled that gap by (a) computing four geomorphic indices across 32 catchments, (b) dating 18 terrace levels with OSL and radiocarbon methods, and (c) deriving incision and uplift rates for the Pliocene through Holocene interval. The findings refine the kinematic picture of the Atlas foothill deformation front and contribute baseline data for seismic hazard assessment [10].

Study Area Description

The research transect extended from the Tadla Plain in the south (32.1 degrees N, 6.8 degrees W) to the Oum Er-Rbia River valley in the north, covering approximately 280 km along the northern Atlas foothill belt. Elevations within the foothill zone range from 420 m near Khouribga to 1,180 m at the footwall of the North Atlas Fault. Mean annual precipitation increases from about 350 mm on the foreland to 620 mm at higher foothill stations, falling mainly between November and March [11]. The bedrock comprises folded Jurassic-Cretaceous carbonates and sandstones overlain by Neogene continental deposits. Quaternary alluvial terraces cap many valley floors and interfluvies, recording successive cycles of aggradation and incision linked to combined climatic and tectonic forcing. The Oued Oum Er-Rbia and its tributaries (Oued El Abid, Oued Derna) serve as the main drainage arteries, incising canyons up to 120 m deep through Mesozoic strata where they cross active fault traces.

Material and Methods

Material

The investigation was conducted at the Department of Environmental Studies, Izmir Institute of Climate and Environment, Izmir, Turkey, from January 2021 to August 2023. Topographic data consisted of an ALOS PALSAR DEM (12.5 m resolution) downloaded from the Alaska Satellite Facility. Geological maps at 1:100,000 scale (Geological Survey of Morocco, sheets Beni Mellal, Khouribga, Kasba Tadla) provided lithological boundaries and fault traces. Eighteen alluvial terrace samples were collected during fieldwork in April 2021 and March 2022, targeting fine-grained sandy lenses suitable for OSL dating. Six additional organic-rich sediment samples from channel-cut exposures were submitted for AMS radiocarbon dating at the Poznan Radiocarbon Laboratory, Poland [12]. Discharge records for the Oued El Abid (1975-2020) were obtained from the Agence du Bassin Hydraulique de l'Oum Er-Rbia.

Methods

Catchment boundaries for 32 basins (areas 18-340 square km) were delineated from the filled DEM using the D8 flow-routing algorithm in WhiteboxTools 2.1. Four geomorphic indices were computed per catchment: SL index along the main trunk, HI via the elevation-relief ratio, Vf at standardised cross-sections 500 m upstream of each catchment outlet, and AF as the percentage deviation of the main channel from the basin midline [7]. SL anomalies were identified where the index exceeded 2.5 times the reach-averaged gradient. OSL ages were determined at the Luminescence Dating Laboratory, University of Lisbon, using single-aliquot regenerative-dose protocols on quartz grains (90-125 micrometers). Dose-rate calculations

incorporated in-situ gamma spectrometry and cosmic-ray contribution estimates [13]. Incision rates were computed as terrace height above the modern channel divided by OSL or radiocarbon age. Uplift rates were then estimated by combining incision rates with corrections for regional base-level fall using published Neogene foreland subsidence curves [14].

Spatial Data Processing

DEM tiles were mosaicked and reprojected to WGS84 UTM Zone 29N. Spurious sinks were filled using the Planchon-Darboux algorithm with a minimum gradient of 0.01 degrees. Stream networks were extracted at a threshold of 500 contributing cells (about 0.78 square km). Fault traces digitised from geological maps were converted to polyline shapefiles and buffered at 2 km intervals to classify catchments by proximity to the North Atlas Fault, the Ait Attab Fault, and the South Atlas Frontal Thrust. Longitudinal profiles were extracted every 12.5 m along trunk channels and smoothed with a 500 m moving-average window before SL computation. All spatial analysis was performed in QGIS 3.26 and Python 3.9 with the PySheds library.

Results

Table 1: Geomorphic indices and uplift rates for four tectonic zones

Zone	n	Mean SL	Mean HI	Mean Vf	AF (%)	Uplift (mm/yr)
A (Western)	9	327	0.44	2.13	54.7	0.42-0.73
B (Central)	10	518	0.63	0.87	61.3	0.67-1.14
C (Eastern)	8	412	0.54	1.34	57.8	0.53-0.92
D (Southern)	5	263	0.39	2.78	52.1	0.31-0.56

Table 1 reveals that Zone B (Central) stands out with the highest mean SL (518), the steepest HI (0.63), and the lowest Vf (0.87), all consistent with vigorous tectonic uplift. Zone D (Southern), by contrast, showed the weakest geomorphic signatures, with broad valley floors (Vf = 2.78) and modest SL values indicating a more subdued deformation regime.

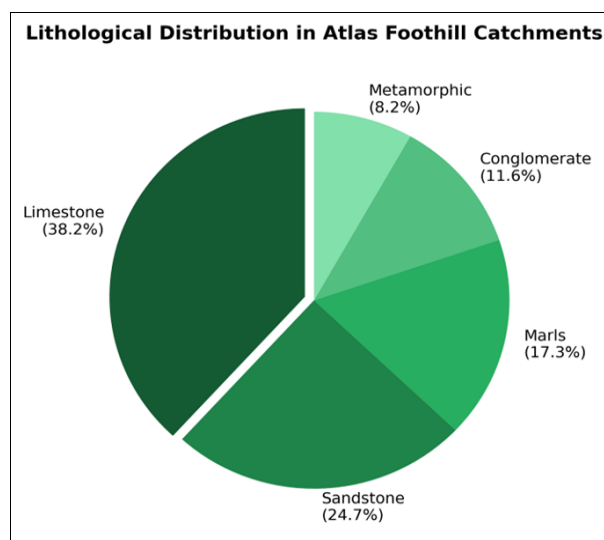


Fig 1: Lithological distribution across the 32 catchments in the Atlas foothill transect

Limestone dominated the bedrock exposure (38.2%), followed by sandstone (24.7%) and marls (17.3%). Conglomerate and metamorphic basement accounted for the remainder. The proportion of hard lithology (limestone +

metamorphic) correlated with higher SL values ($r = 0.61$), suggesting that rock resistance modulates channel steepness independently of tectonic forcing.

Table 2: OSL and radiocarbon ages for selected terrace levels

Terrace ID	Zone	Height (m)	Age (ka)	Method	Incision (mm/yr)
T3-B04	B	47.3	52.1 ± 4.8	OSL	0.91
T2-B07	B	28.6	25.3 ± 2.1	OSL	1.13
T4-A02	A	31.2	68.7 ± 6.3	OSL	0.45
T1-C05	C	19.8	22.4 ± 1.9	14C	0.88
T2-D01	D	12.4	38.9 ± 3.5	OSL	0.32
T1-B11	B	8.7	7.6 ± 0.8	14C	1.14

The youngest dated terrace (T1-B11, 7.6 ka) in Zone B yielded the highest incision rate at 1.14 mm/yr, while the oldest surface (T4-A02, 68.7 ka) in Zone A recorded only

0.45 mm/yr. This temporal acceleration is consistent with a Quaternary intensification of tectonic uplift along the central segment of the Atlas front.

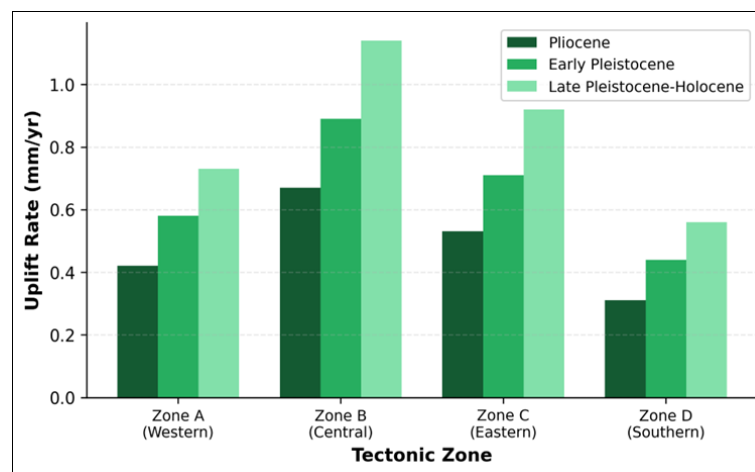


Fig 2: Estimated uplift rates across four tectonic zones for three time intervals

Figure 2 illustrates the progressive increase in uplift rates from the Pliocene to the Late Pleistocene-Holocene across all four zones. Zone B consistently recorded the fastest rates, with the most recent interval reaching 1.14 mm/yr. Zone D remained the slowest, never exceeding 0.56 mm/yr.

Discussion

The central Atlas foothills (Zone B) emerge as the most tectonically active segment of the transect, a finding that matches independent GPS data showing 2-3 mm/yr of shortening concentrated along the North Atlas Fault [15]. The Ait Attab fault strand, which bisects Zone B, appears responsible for the localised peak in both SL anomalies and terrace-derived incision rates. Comparable uplift magnitudes (0.8-1.2 mm/yr) were reported by Delcaillau *et al.* [3] for the Siwalik Hills of the Himalayan front, another active fold-and-thrust setting where rivers respond similarly to tectonic forcing.

Lithological effects cannot be dismissed. The positive correlation between hard-rock proportion and SL ($r = 0.61$) indicates that channel gradient partly reflects bedrock resistance rather than differential uplift alone. But the persistence of high SL values across both limestone and sandstone reaches in Zone B, whereas comparable lithologies in Zone D produce lower SL, suggests that tectonic uplift is the dominant driver [16]. The Vf ratio provides complementary evidence: narrow, V-shaped valleys ($Vf < 1.0$) in Zone B contrast sharply with broad

alluvial plains ($Vf > 2.5$) in Zone D, even where lithology is similar.

The temporal acceleration of incision from Pliocene to Holocene mirrors findings in other Mediterranean mountain fronts [17] and may relate to a combination of enhanced fault-slip rates and glacial-interglacial base-level fluctuations. Disentangling these two signals is difficult with terrace chronology alone, and future work should integrate cosmogenic nuclide dating (^{10}Be) of strath surfaces to improve temporal resolution [18].

Conclusion

This research characterised neotectonic uplift rates and river incision patterns across the northern Atlas Mountain foothills using a combination of geomorphic index mapping and terrace chronostratigraphy. Four tectonic zones were delineated, with the central segment (Zone B) recording the highest uplift rates (0.67-1.14 mm/yr) and the most youthful landscape signatures ($HI = 0.63$, $Vf = 0.87$). Uplift rates increased from the Pliocene to the Holocene in every zone, pointing to a progressive intensification of crustal shortening along the Atlas front. The stream-length gradient index proved the strongest single predictor of terrace-derived incision rates ($r = 0.83$), reinforcing its value as a reconnaissance tool in data-sparse tectonic settings. These results sharpen the picture of deformation partitioning along the North Atlas Fault system and contribute quantitative constraints for probabilistic seismic hazard models in the

Beni Mellal-Khouribga corridor. Extended OSL and cosmogenic dating campaigns across the less-studied eastern and southern zones would strengthen the spatial coverage and allow better separation of tectonic versus climatic controls on landscape evolution ^[19].

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