Morphostructural Analysis and Active Tectonics of the Northeastern Constantine Basin, Algeria: Insights from Morphometric Indices and Structural Lineaments

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Abstract
Since their formation, the Maghrebids have been influenced by major tectonic movements in geological history. These events have resulted in morpho-structural arrangements that are still poorly understood, particularly in the northeastern of the Constantine Basin. This study aims to fill this gap with an integrated morpho-structural analysis, based on: (i) detailed field mapping, (ii) detailed lineament analysis based on aerial and satellite imagery, and (iii) the calculation of quantitative geomorphological indices grouped in the IRAT (Indice de Tectonique Active Relative). Seven morphometric indices were extracted from a 10 m resolution DTM and applied to the Kef Hahouner (KHB) and Guendoula Messigla (GMB) watersheds. These are the hypsometric integral (H_i), mountain front sinuosity (S_{mf}), valley floor width/height ratio (V_f), asymmetry factor (A_f), basin shape index (B_s), transverse topographic symmetry factor (T) and stream length gradient (S_L). The ENE-WSW trending Kef Hahouner-Aïn Berda (KHAB) sinister strike-slip fault crosses both basins. It constitutes the main structure, identified through more than 500 lineaments, accompanied by more recent faults oriented N-S and NW-SE. The average IRAT S/N score is 2.0, classifying the zone as class 3 (moderate activity). However, several indicators suggest that this moderate classification is underestimated: S_L values exceed 600, V_f ratios are below 0.5, the S_{mf} of the KHB mountain front is 1.11, and A_f values indicate asymmetrical basin tilting. In addition, the low B_s values (1.43-1.58) seem to testify to tectonic control. This suggests that the IRAT probably underestimates the actual level of activity. By combining morphometric data with GIS and field measurements of offset geomorphic markers, the area was reclassified as class 2 (high activity). Our results show that an active fault corridor strongly modifies drainage, relief generation and sediment dynamics. They underline the importance of combining geomorphological indicators with structural analysis to improve neotectonic assessments in structurally complex regions.

Keywords: Active Tectonics, Constantine Basin (NE Algeria), IRAT Method, Morpho-Structural Analysis, Strike-Slip Faults

1. Introduction

It is difficult to grasp how the Earth's surface has changed throughout time since tectonic processes and erosional dynamics are always competing with one other. This interaction is very important for sculpting landscapes and regulating the shape of both active and ancient geological structures. To understand where geomorphological features came from and how they changed over time, we need to use a variety of fields, including tectonic theory, geomorphic observation, and structural analysis.

Many different schools of thought have tried to explain how tectonics and erosion shape and change landscapes over the course of the 20th century. [1] is among of the first people to work in this field. Their ideas about how landscapes change over time were the basis for later geomorphic theory.

Later researchers, like [2], who created quantitative tools for measuring neotectonic activity in dry areas, and [3][4][5][6] and [7], who each added ways to measure active tectonics using morphometric indices and structural indicators, improved these classical models [8].

Advances in geospatial technologies, in particular the widespread adoption of remote sensing and Geographic Information Systems (GIS) in geological research, have greatly enhanced our ability to analyze morpho-tectonic structures. The integration of high-resolution satellite images, Digital Elevation Models (DEMs) and specialized software such as ArcGIS and ENVI enables precise mapping of tectonic lineaments, topographic anomalies and hydrographic networks. These tools have fostered the development of quantitative morphometric methodologies, capable of detecting tectonic clues often inaccessible by conventional field methods [9][10] and [11].

In this context, the Index of Relative Active Tectonics (IRAT) has emerged as an effective method for assessing recent tectonic activity through a combination of geomorphological indices. IRAT includes parameters such as hypsometric integral (*HI*), mountain front sinuosity (S_{mf}), valley floor width/height ratio (V_f), longitudinal stream slope index (S_L), basin asymmetry factor (A_f), basin shape index (B_s) and transverse topographic symmetry factor (*T*). Together, these indices offer an integrated framework for identifying and prioritizing active tectonic deformation at the watershed scale [12][13] and [14]. When coupled with field observations and structural mapping, this approach enables a robust interpretation of the spatio-temporal evolution of tectonic structures [10][11][15] and [16].

The present study focuses on the morpho-structural organization of the northeastern sector of the Constantine Basin, located in northeastern Algeria. This geologically complex region remains little explored and insufficiently integrated into regional tectonic syntheses [9][17] and [18]. The chosen study area goes from Kef Hahouner to Ain Berda. This boundary is not random; it is based on the first results of a structural and lineament investigation that showed a large left-lateral strike-slip fault system [19]. This fault, which we will call the KH-AB Fault (Kef Hahouner–Ain Berda Fault), runs for several kilometers and seems to have a big effect on the drainage and morpho-structural aspects in the area.

The research area has three main drainage basins: the Kef Hahouner Basin (KHB), and Guendoula–Messigla Basin (GMB), which goes toward the Ain Berda region [20]. We chose the KHB and GMB basins for in-depth morphometric and structural analysis for this work because they show active tectonic characteristics more clearly and have more data available [12] and [21]. Field observations, along with aerial picture interpretation and lineament mapping, have shown that strike-slip deformation leaves behind certain signs, such as bent drainages, fault scarps, aligned springs, and valleys that aren't symmetrical [22]. This study attempts to make it clearer how tectonic processes shape the morpho-structural framework of this part of the Maghrebides by combining field evidence with the IRAT approach and remote sensing data. In the end, this investigation helps us learn more about the tectonics of northeastern Algeria and gives us important information about how the Constantine Basin is changing geologically at present.

2. Materials and Methods

2.1 Geographical Setting of the Study Area

The study area is located at the extreme northeastern edge of the Constantine Basin in northeastern Algeria (Figure 1). It encompasses a major sinister strike-slip fault system, hereinafter referred to as the KH-AB fault (Kef Hahouner-Aïn Berda fault), which extends over more than 30 kilometers, from the southern sector of Kef Hahouner to the Aïn Berda region, and probably beyond, in a northeasterly direction. This fault system constitutes a major structural discontinuity within the Maghreb chain, controlling both regional morphology and the organization of the area's watersheds. In order to better understand the morpho-structural dynamics associated with the KH-AB fault, the analysis was structured according to the natural and morpho-geological subdivision of the terrain [9][15] and [23]. This segmentation reveals the presence of three main drainage basins, together forming the structural mosaic associated with the fault system (Figure 2).

The selected basins (KHB and GMB) are ideal structural domains for examining the influence of strike-slip tectonics on the evolution of the regional landscape. From west to east, these basins are:

- Kef Hahouner Basin (KHB): This basin corresponds to the western segment of the KH-AB fault zone. It is bounded to the north by Djebel Boutelis, to the south by the Ouled Hbaba forest, to the west by Douar Ouled Hamza and to the east by Oued Zoubia - a geologically significant linear structure, oriented approximately N12°. The total surface area of the basin is approximately 96 km². The internal structure and topographic configuration of the KHB are strongly influenced by fault-related deformation and lithological contrasts.

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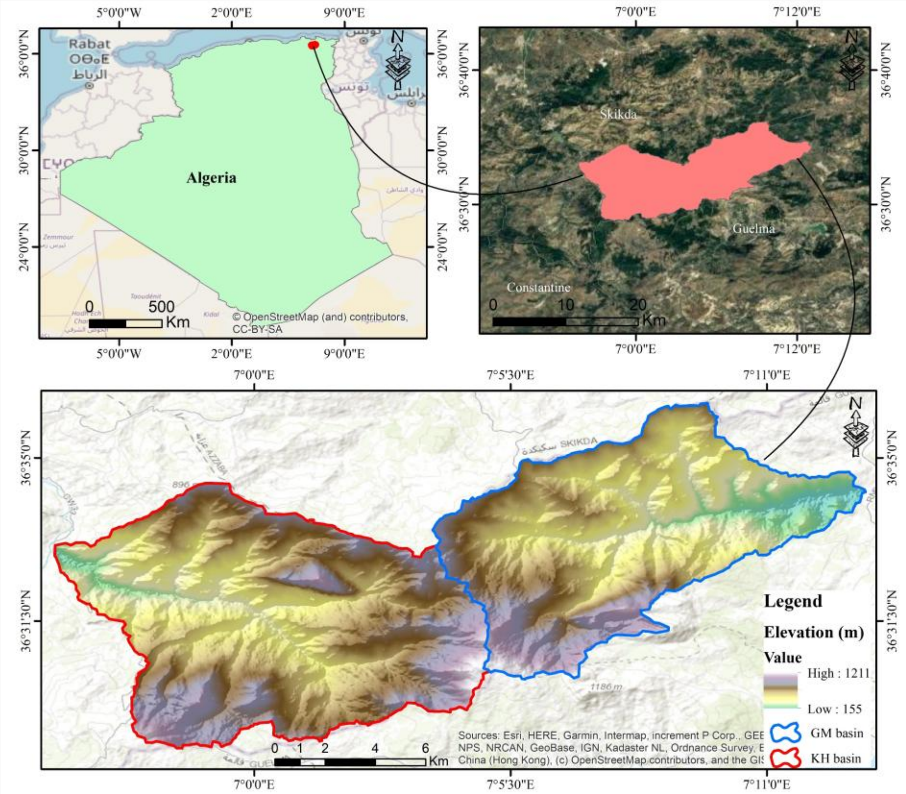

Figure 1: Location map of the Kef Hahouner–Djebel Debar (KH) and Guendoula–Messigla (GM) basins

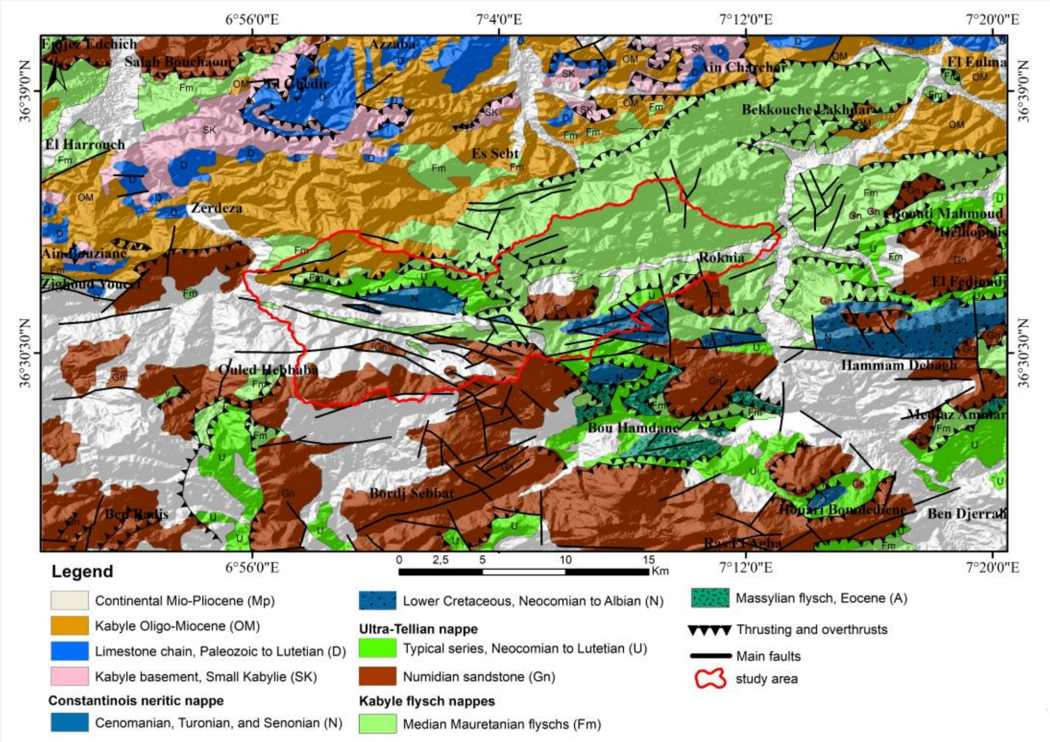

Figure 2: Geological map of the study area

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- Guendoula-Messigla basin (GMB): Located immediately to the east of the KHB, this basin is bounded to the west by the Oued Zoubia and to the east by the Oued Roknia, a fault-guided watercourse with a marked north-south orientation. The southern boundary is formed by Djebel El Grar, while the northern end reaches Douar El Grhar. Covering an area of around 76 km², this basin is clearly structurally controlled by the fault system, as evidenced by the aligned valleys, steep lithological contacts and linear escarpments.

The clear tectonic footprints and accessible geomorphological features of these basins make them particularly suitable for morphometric analysis and assessment of fault activity. This spatial framework supports the overall objective of understanding how the KH-AB fault system helped shape the morpho-structural identity of the northeastern Constantine Basin.

2.2 Geological and Structural Framework

The study area located in the Algerian Tell, a structurally complex segment of the Maghreb chain, as described in detail by Raoult. It comprises a diverse array of lithological units that reflect the main stages in the region's tectonic-sedimentary evolution. Mauretanian Flysch is the oldest sequence, composed of radiolarites (Dogger-Malm), topped by Tithonian-Neocomian limestones, Barremian sandstones and polychrome Aptio-Albian clays [24]. The overlying Neretic series, mainly limestone, extends from Neocomian to Senonian and rests unconformably on Upper Jurassic dolomites. To the north of the Tellian Basin lies the Massylian Flysch, which is underlain by Aptian-Albian clays, followed by Cenomanian conglomerates and an upper sequence of Senonian marly breccias [24]. The Numidian Flysch (Oligocene-Burdigalian) consists of thick sub-Numidian clays, massive sandstone beds and supra-Numidian clays. The continental Miocene is characterized by basal conglomerates evolving towards clayey facies (Middle-Upper Miocene) (Figure 2).

A huge volcanic complex, outcropping south of the Oued Mira, consists of flows ranging from lamproite to shoshonite, testifying to localized post-orogenic magmatism [25]. Tectonically, the region has been shaped by several phases of deformation. The earliest movements, which occurred during the Jurassic, Cretaceous and Paleocene periods, are locally preserved. However, the tangential deformations of the Upper Lutetian and the compressive events of the late Oligocene to early Aquitanian had a more significant impact, being at the origin of major thrust systems.

Raoult has also highlighted persistent neotectonic activity from the Upper Burdigalian to the Quaternary, manifested in folding and an east-west oriented fault network (normals, inverses and detachments). These neotectonic episodes reworked the previous nappes and profoundly influenced the regional topography. A major structural element is the Kef Hahouner-Djebel Debar fault, a normal fault with a vertical rejection of around 3,000 meters and a length exceeding 100 km, active since at least the Middle Miocene. It plays a central role in the morpho-structural dynamics of the Constantine Basin. This study aims to deepen our understanding of its implications through an integrated geomorphological and structural analysis.

3. Results

3.1 Morphometric Analysis

To assess tectonic activity in the study area, we applied the Index of Relative Active Tectonics (IRAT), a quantitative method based on geomorphological indicators derived from Digital Elevation Models (DEMs). The methodology adopted in this study was implemented in a GIS environment, enabling the integration of several morphometric parameters reflecting the joint effects of tectonic activity and erosion processes. More specifically, seven key geomorphological indices were selected for analysis: hypsometric integral (H_i), mountain front sinuosity (S_{mf}), valley floor width/height ratio (V_f), basin asymmetry factor (A_f), basin shape index (B_s), transverse topographic symmetry factor (T) and longitudinal stream slope index (S_L). These indices were calculated and compiled in a geodatabase, serving as the basis for calculating the Index of Relative Active Tectonics (IRAT). For detailed analysis, two representative basins - Kef Hahouner (KHB) and Oued Guendoula-Oued Mssigla (GMB) - were selected.

3.1.1 Hypsometric integral (H_i)

A central element of this assessment is the hypsometric integral (H_i), a dimensionless index that quantifies the proportion of a watershed's volume that remains un-eroded. Initially conceptualized by [7] and then refined by [26] and [27], this index is a valuable indicator for determining the degree of geomorphological maturity of a basin and for inferring possible tectonic influences. The hypsometric integral is calculated using Equation 1:

$$H_i = \frac{H_{mean} - H_{min}}{H_{max} - H_{min}}$$

Equation 1

Where:

H_{mean} is the mean elevation of the basin
H_{min} is the minimum elevation
H_{max} is the maximum elevation

In this study case, the "mean" elevation was derived from 50 randomly distributed points within each basin (GMB and KHB).

The hypsometric curve, which represents relative altitude as a function of cumulative surface area, is a complementary indicator of the degree of erosion maturity of a watershed. Three evolutionary stages can be distinguished:

- a young stage ($H_i > 0.5$), characterized by upward concave curves;
- a mature stage (H_i between 0.4 and 0.5), associated with sigmoid curves;
- an old stage ($H_i < 0.4$), with downward convex profiles.

S-shaped hypsometric curves are generally associated with tectonically active basins undergoing rejuvenation [28] and [29]. Our analysis revealed sigmoidal hypsometric curves for the two basins studied (KHB and GMB), with H_i values of 0.49 in both cases (Figure 3). These values reflect a transitional stage between youth and maturity, suggesting active but not extreme incision processes. Note that both curves show a convex lower segment, which could reflect recent tectonic uplift, possibly along fault lines, as suggested by [4] and [30].

These morphological signatures suggest that the basins studied are still undergoing structural readjustment, in line with regional neotectonic trends highlights the influence of active tectonics, probably modulated by lithological resistance and climatic conditions. The hypsometric analysis thus corroborates the hypothesis of ongoing deformation in the study area, particularly along the Kef Hahouner-Djebel Debar fault system. This morphometric assessment, combined with regional structural data, provides a relevant analytical framework for assessing tectonic activity and landscape evolution in the northeastern Constantine Basin.

The mountain front sinuosity index (S_{mf}) is a relevant geomorphological parameter for assessing the dynamic balance between erosion processes and tectonic uplift along mountain fronts. When erosion is dominant, it tends to soften and notch the mountain front, increasing its sinuosity. In this case, foothill areas extend further from the ridge towards the plain, and S_{mf} values are relatively high. Conversely, in areas where tectonics predominate, the relief is more rectilinear, less eroded and steeper - all characteristics indicative of active uplift and young topography. These contexts are generally reflected in low S_{mf} values. According to [31] and [32], S_{mf} values below 1.4 indicate tectonically active fronts, while values above 3 are characteristic of inactive or fossil fronts, where the original fault may be offset by more than a kilometer from the present erosional front [33]. The classification of *Smf* values are clssified into three classes [4]:

- Class 1: $S_{mf} < 1.1$ is high tectonic activity;
- Class 2: $1.1 \le S_{mf} < 1.5$ is moderate activity;
- Class 3: $S_{mf} \ge 1.5$ is low activity or dominant erosion.

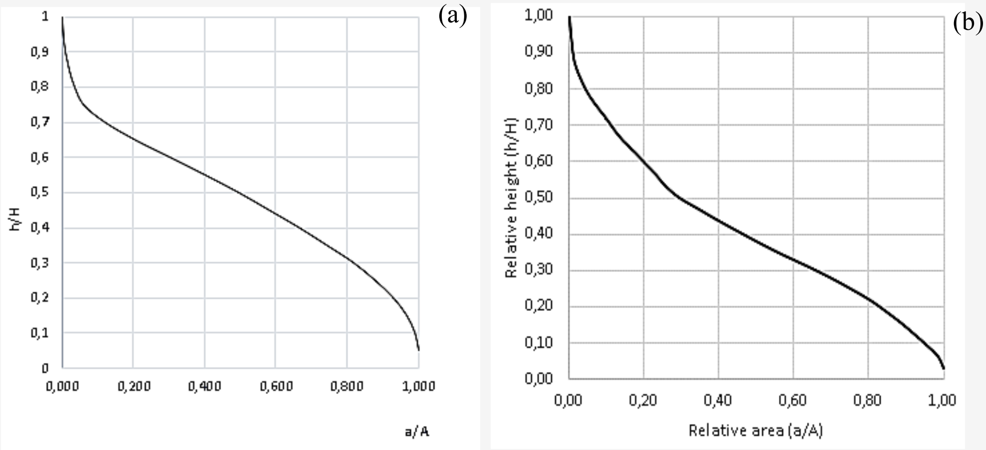

Figure 3: Hypsometric curves for the basins: (a) KHB, and (b) GMB

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3.1.2 Mountain front sinuosity index (S_{mf})

The S_{mf} index is also recognized as a key indicator of relative tectonic activity [32], particularly when used in conjunction with other morphometric parameters such as stream gradient indices. It should be noted that not all active fronts necessarily feature well-marked triangular facets, although their presence - particularly when they result from repeated fault activity at the base of escarpments - is a strong indicator of active tectonics [34]. Sparsely dissected, linear escarpments or quasi-continuous fronts with a few well-developed triangular facets are typical of the most active zones [35]. The S_{mf}index, originally introduced by [36] is calculated according to Equation 2:

$$S_{mf} = \frac{L_{mf}}{L_s}$$

Equation 2

Where:

S_{mf} is the inuosity index of the mountain front,
L_{mf} is the actual length of mountain front measured along its natural course,
L_s is the straight-line length of mountain front.

S_{mf}values can be extracted from topographic maps or aerial images. However, the accuracy of the results depends on the scale of the source used: small-scale maps provide only rough estimates, while large-scale maps and high-resolution images enable more precise measurement.

In our study area, the S_{mf} index was calculated along the southern front of Mount Kef Hahouner, within the KHB basin (Figure 4). This well-marked, NE-SW-trending escarpment rises more than 300 metres above Quaternary alluvial fan deposits up to 30 metres thick. The value obtained for S_{mf} = 1.1 (< 1.4) reveals an actively uplifting mountain front, corresponding to class 2, close to class 1, indicating a significant tectonic influence. Field observations to the north of Oued Khmekhem, at the junction of the Smendou (no. 52) and Hammam El Meskoutine (no. 53) geological map sheets, west of Kef Hahouner, have revealed the presence of well-developed triangular facets, exceeding in size the associated alluvial fans. This morphology is typically associated with active normal faults. By correlating these elements with the results of the S_{mf} index, it becomes clear that the Kef Hahouner-Djebel Debar fault is an active normal fault, playing a major role in regional neotectonic deformation.

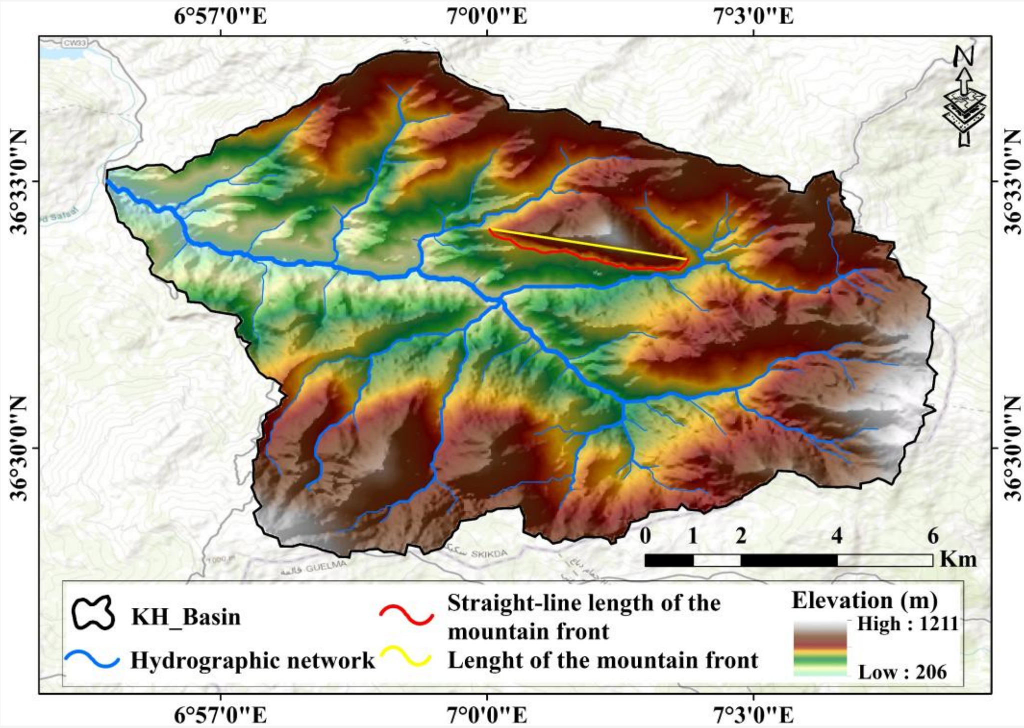

Figure 4: Sinuosity Index (S_{mf}) of the Kef Hahouner Mountain in the (KHB) basin

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3.1.3 Valley floor width-to-height ratio (V_f)

The *Vf* index is a morphometric parameter used to differentiate V-shaped valleys, generally associated with active tectonic uplift, from U-shaped valleys, which reflect a period of tectonic calm. Although V_f primarily measures valley incision rather than uplift per se, under equilibrium conditions, incision and uplift rates are often correlated [4]. Low V_f values (< 1) indicate narrow, V-shaped valleys undergoing active incision in response to tectonic uplift. Conversely, high V_f values (> 1) characterize wider, U-shaped valleys, shaped by dominant lateral erosion, often in connection with a stable base level or reduced tectonic activity [7]. The valley floor width-to-height ratio (V_f) is a commonly used morphometric indicator for assessing tectonic activity. V_f values are divided into three classes [4]:

- Class 1 ($V_f < 0.5$), corresponding to high tectonic activity and marked incision;
- Class 2 ($0.5 \leq V_f < 1$), reflecting moderate tectonic activity;
- Class 3 ($V_f \geq 1$), associated with low tectonic activity and widened valley floors.

It has also been observed that valleys tend to narrow upstream of mountain fronts [28]. However, V_f values can be influenced by various geomorphological and lithological factors, including basin size, river flow, and the nature of geological formations [37]. Despite these variables, the V_f index remains a relevant indicator for assessing the relative degree of tectonic activity [38]. The index V_f is calculated using Equation 3:

$$V_f = \frac{2V_{fw}}{E_{ld} + E_{sc}} + E_{rd} - E_{sc}$$

Equation 3

Where:

V_{fw} is the valley floor width

E_{ld} and E_{rd} are the altitudes of the left and right interfluves, respectively,

E_{sc} is the altitude of the valley floor or river bed

In this study, the Kef Hahouner–Djebel Debar (KHB) basin was subdivided into four segments of 3 km each, while the Guendoula–Mssigla (GMB) basin was divided into four segments of 1.8 km (Figures 5 and 6) topographic profiles (Figures 7 and 8). Analysis of the calculated V_f index values reveals the following trends:

In the KHB basin, V_f values range from 0.05 to 0.5 (<1), reflecting marked incision and relatively high tectonic activity, particularly in the middle and downstream segments.

In the GMB basin, V_f values range from 0.18 to 0.68 (<1), indicating moderate tectonic activity, with a more pronounced tectonic influence in the central zone compared to the upstream and downstream sections.

In conclusion, the V_f indices obtained for both basins (KHB and GMB) show predominantly V-shaped valley profiles. Although the downstream sections show a slight tendency towards valley widening, lateral erosion remains limited overall. These results confirm that both basins are subject to active tectonic uplift.

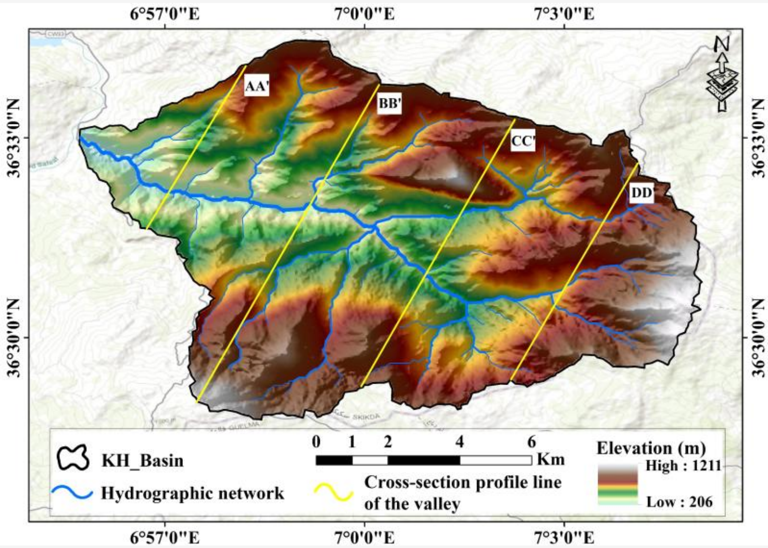

Figure 5: Zone division (KHB) area

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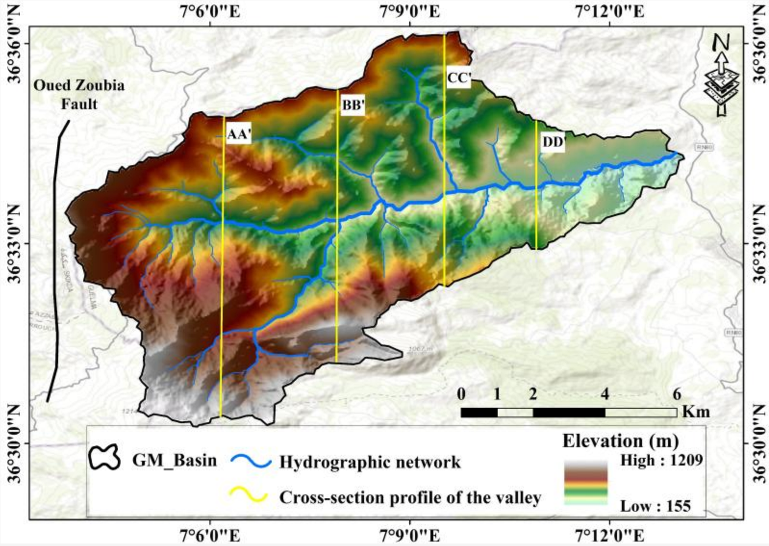

Figure 6: Zone division (GMB) area

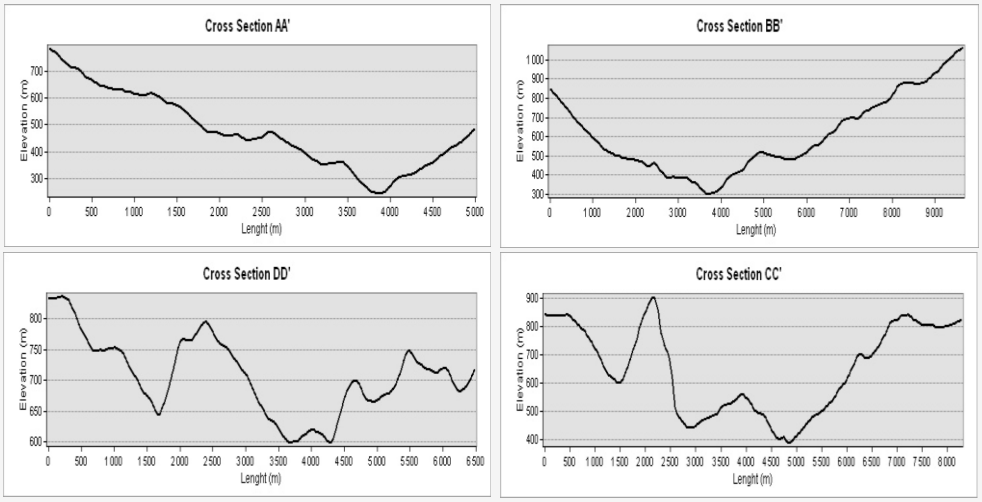

Figure 7: Cross-sections of (KHB)

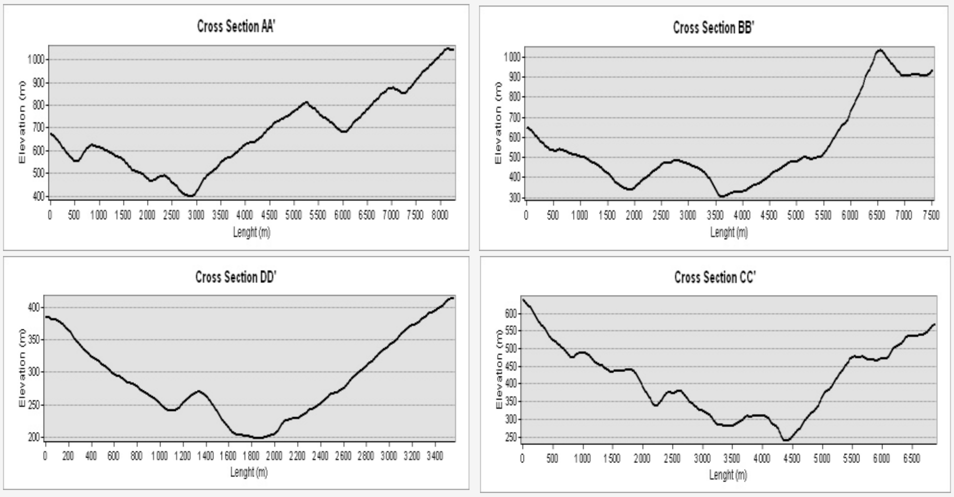

Figure 8: Cross-Sections of the (GMB) basin

3.1.4 Asymmetry Factor (A_f)

The asymmetry factor (A_f) is an essential morphometric indicator for assessing the presence of tectonic tilting at watershed scale. This method is applicable to relatively large areas [6] and [39]. Drainage basin tilting can result from fault-related tectonic movements, as observed in many fluvial systems [31] and [40]. In tectonically stable contexts, A_f values are generally close to 50. Values significantly above or below this threshold are interpreted as possible signs of tectonic tilting [6]. However, these interpretations need to be qualified, as deviations from 50 can also be the result of differential erosion or structural and lithological control, such as displacement of the riverbed within stratified plains over geological time [4]. According to the classification proposed by [41], A_f values are distributed as follows:

- Class 1: $A_f < 35$ or $A_f \geq 65$
- Class 2: $35 \leq A_f < 43$ or $57 \leq A_f < 65$
- Class 3: $43 \leq A_f < 57$

The asymmetry factor is calculated using Equation 4:

$$A_f = \frac{A_r}{A_t} \times 100$$

Equation 4

Where:

A_r is the area of the right side of the basin (looking downstream),

A_t is the total surface area of the basin.

Analysis of the study area shows that the KHB basin has an A_f value of 53.54, indicating rightward tilt, while the GMB basin has a value of 48.38, indicating leftward tilt (Figures 9 and 10). This opposite tilting on either side reinforces the hypothesis of the existence of a major senestial strike-slip fault, the Oued Zoubia fault, oriented N12, which seems to control the deformations affecting the two basins (KHB and GMB).

3.1.5 Basin shape index (B_s)

The watershed shape index (B_s) is used to assess the morphology of a drainage basin. A low value of B_s indicates a circular shape, while higher values reflect an elongated morphology. According to the classification proposed by [37] and [42], this index is divided into three classes:

- Class 1: $B_s \geq 4$
- Class 2: $3 \leq B_s \leq 4$
- Class 3: $B_s \leq 3$

In tectonically stable or gradually evolving contexts, initially elongated basins tend to adopt a more circular shape over time [36]. On the other hand, in tectonically active areas, relatively young basins generally have an elongated shape, oriented perpendicular to the topographic slope of the mountain front [4].

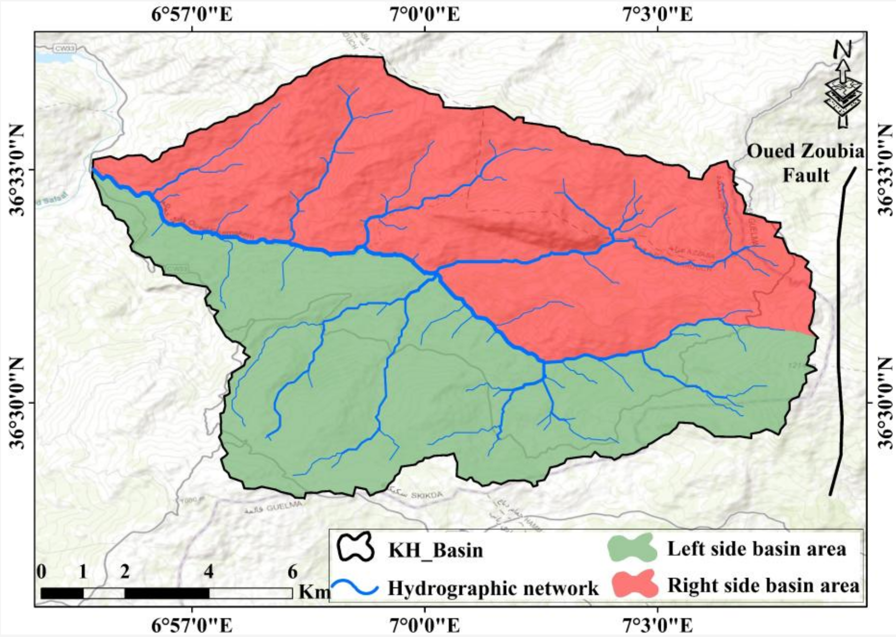

Figure 9: Asymmetry factor (A_f) of the (KHB) basin

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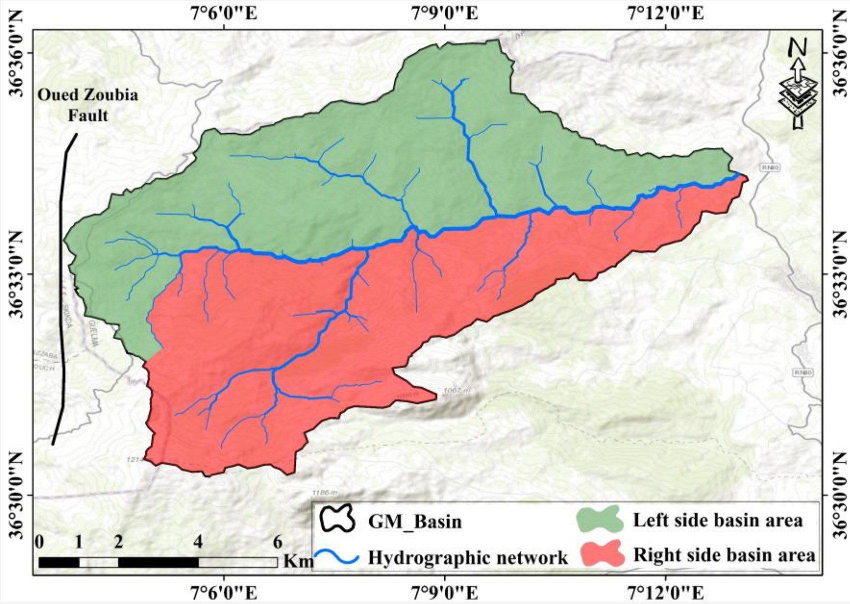

Figure 10: Asymmetry factor (A_f) of the (GMB) basin

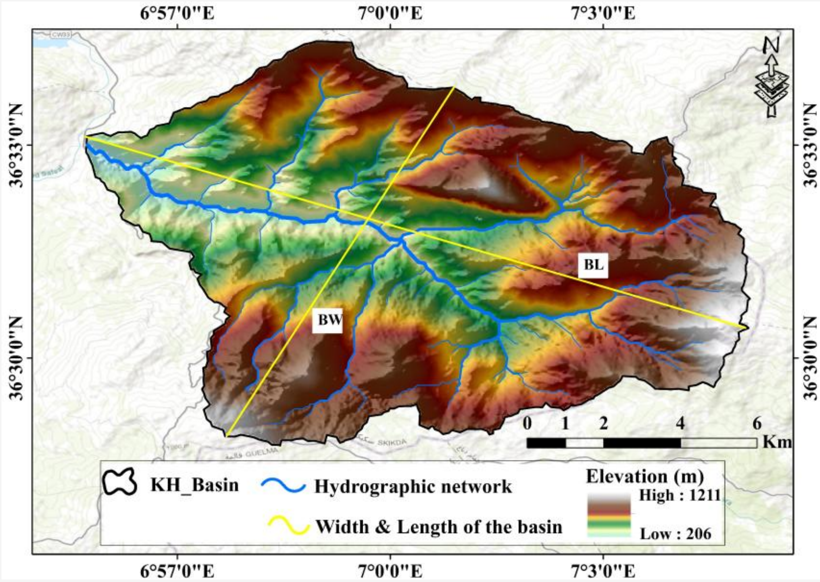

Figure 11: Form factor Index (Bs) of the (KHB) basin

In these active environments, basin widths are often reduced close to the mountain front, where Stream Energy is dominated by active tectonic uplift. Conversely, in the absence of significant and continuous tectonic uplift, basin width tends to widen upstream of the mountain front [28]. The B_s index is calculated using Equation 5 [36]:

$$B_s = \frac{B_i}{B_W}$$

Equation 5

Where:

B_l is the length of the basin, measured from the source to the outlet.

B_w is the maximum width of the basin (Figures 11 and 12).

In our study, the B_s values calculated for the two basins analyzed - KHB and GMB - are 1.43 and 1.58 respectively. These relatively low values indicate a moderately active tectonic regime influencing the morphology of the basins.

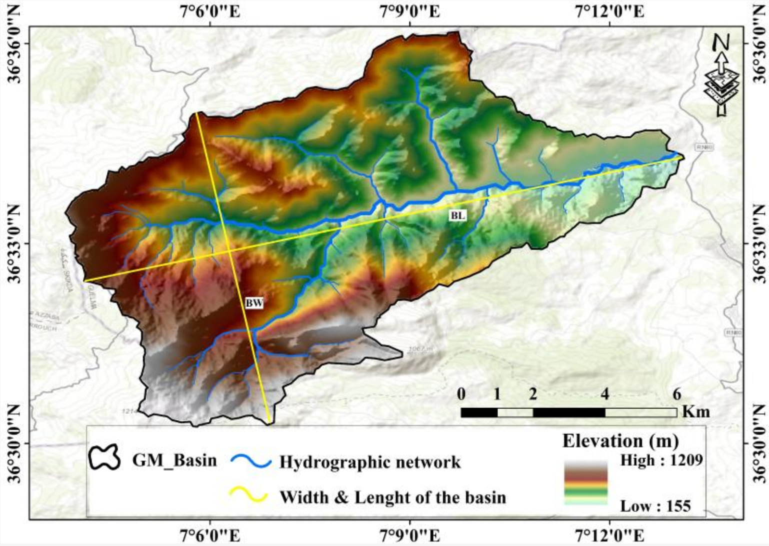

Figure 12: Form factor index (B_s) of the (GMB) basin

3.1.6 Topographic transverse symmetry factor (T)

The transverse topographic symmetry factor (*T*) is a quantitative geomorphological index used to assess the lateral symmetry of a watershed. It is particularly useful for detecting lateral migrations of the main channel relative to the central longitudinal axis of the basin. When the watercourse moves away from this axis towards one of the edges of the basin, the value of *T* increases and tends towards 1 [28]. Initially introduced by [43], this index quantifies the spatial offset of the main channel. It is a relevant indicator for highlighting possible neotectonic influences, particularly in areas where active faults are not very visible or are hidden under Quaternary deposits. *T* values range from 0 to 1. A value close to 0 indicates perfect symmetry, with the river centered between the two edges of the basin, a situation typical of tectonically stable regions. On the other hand, values close to 1 indicate a marked lateral displacement of the channel towards one of the basin's flanks, generally associated with recent or active tectonic deformation [40][44] and [57].

The *T* index is therefore calculated to assess the transverse displacement of the main channel relative to the longitudinal axis of the watershed [6], using Equation 6:

$$T = \frac{D_a}{D_d}$$

Equation 6

Where:

D_a is the distance between the basin centerline and the active meander (current river).

D_d is the distance between the basin centerline and the watershed.

As shown in (Figures 13 and 14), the *T* index provides a better understanding of the spatial layout of the river channel. According to [45], a value of *T* = 0 corresponds to a perfectly symmetrical basin, while values close to 1 indicate increasing asymmetry. *T* values are classified into three classes:

Class 1: $T > 0.4$ (strong asymmetry), Class 2: $0.2 < T \leq 0.4$ (moderate asymmetry), Class 3: $T < 0.2$ (weak asymmetry).

For KHB basin, *T* values range from 0.03 to 0.20, placing it in class 3. In contrast, values for GMB basin range from 0.008 to 0.675, reflecting a wider range of asymmetry, with several sub-basins falling into class 1 (Figures 13 and 14). These results suggest that both basins show signs of active tectonic deformation, particularly visible through the lateral displacement of drainage networks.

3.1.7 Stream length-gradient index (S_L)

The river longitudinal slope (S_L) index is a morphometric parameter commonly used to assess relative tectonic activity. Its value tends to increase when rivers flow through areas subject to active uplift [46] and [47], and to decrease when they flow parallel to tectonic structures, such as valleys guided by strike-slip faults [32] and [48].

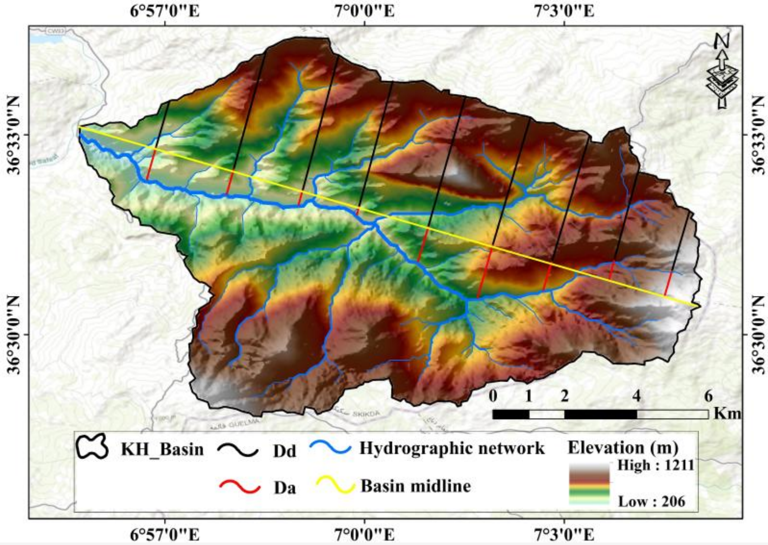

Figure 13: Transverse topographic symmetry factor (T) of the (KHB) basin

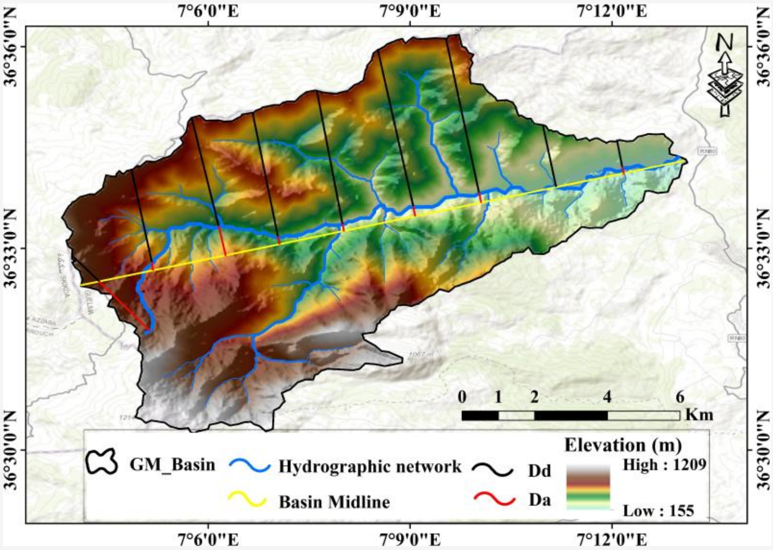

Figure 14: Transverse topographic symmetry factor (*T*) of the GMB basin

Research in the Appalachians (USA) has shown a strong correlation between rock strength and S_L index values, suggesting that landscape morphology is generally well adapted to the underlying lithology. As landforms evolve, stream profiles adjust relatively quickly to rock strength. Thus, abnormally high S_L values, particularly over soft rocks such as shale, may indicate recent tectonic deformation [6] and [49].

Conversely, abnormally low $S_L$values can also reveal tectonic activity. This is particularly the case in linear valleys controlled by strike-slip faults, where rocks crushed by fault movements generate gentler river slopes, resulting in lower S_L values [31] and [50]. In addition, rocks that are homogeneous in terms of strength but exhibit high or highly variable S_L values may also signal tectonic activity [32]. For example, a Bull mountain envelope map reveals a zone of high S_L values between the 200 m and 400 m contour lines for three streams. This anomaly could reflect either the presence of a resistant lithological level, or that of an active fault located on the southern flank of the massif [51] and [52]. According to the classification proposed by [53], S_L values are divided into three classes as follows:

- Class 1: $S_L > 600$
- Class 2: $300 \le S_L \le 600$
- Class 3: $S_L < 300$

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The S_L index is defined in Equation 7:

$$SL = \frac{\Delta H}{\Delta L} L$$

Equation 7

Where:

ΔH is the difference in elevation over a given segment of the watercourse

ΔL is the length of this segment

L is the total length of the channel measured from the middle of the segment to the source

In the basins studied (KHB and GMB), S_L values systematically exceed 600 (Figures 15 and 16). A notable increase in these values is observed as the watercourses pass over loose formations, notably Numidian clays in the KHB basin and Quaternary clays in the GMB basin. These S_L peaks are interpreted as clear signs of recent seismic activity in the region.

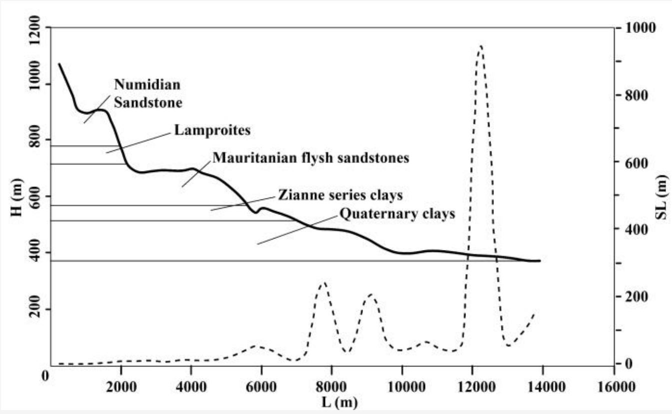

Figure 15: Stream length-gradient index (S_L) for the KHB basin

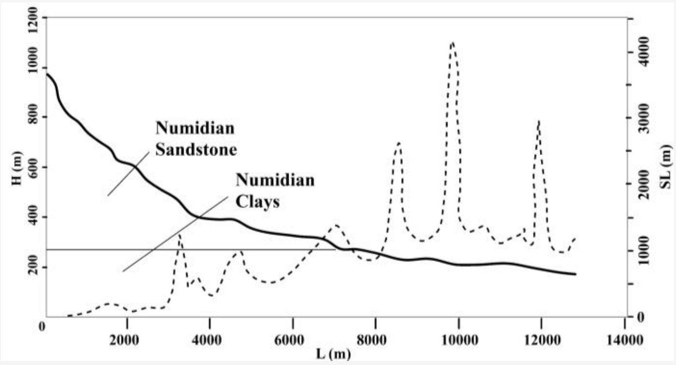

Figure 16: Stream Length-Gradient Index (S_L) for the GMB basin

3.2 Summary Tables

The morphometric indices are presented in Table 1, while Table 2 presents the Morphometric index classification for tectonic activity assessment

Table 1: Summary of morphometric indices reflecting tectonic activity in the KHB and GMB basins

Morphometric Index	(KHB)	(GMB)
Hypsometric Integral (Hi)	49	49
Mountain Front Sinuosity Index (S_{mf})	1.11	–
Valley Floor Width to Valley Height Ratio (V_f)	< 0.5	< 0.5
Asymmetry Factor (A_f)	53.54	48.38
Basin Shape Index (B_s)	1.43	1.58
Stream Length-Gradient Index (S_L)	> 600	> 600

Table 2: Morphometric index classification table for tectonic activity assessment

Morphometric Index	Class		Classification (KHB)	Classification (GMB)
Hypsometric Integral (Hi)	$Hi > 50$	1		
	$40 < Hi \leq 50$	2	2	2
	$Hi < 40$	3		
Mountain Front Sinuosity Index (S_{mf})	$S_{mf} < 1.1$	1		
	$1.1 \leq S_{mf} < 1.5$	2	2	–
	$S_{mf} \geq 1.5$	3		
Valley Floor Width to Valley Height Ratio (V_f)	$V_f < 0.5$	1		
	$0.5 \leq V_f < 1$	2	1	1
	$V_f \geq 1$	3		
Asymmetry Factor (A_f)	($A_f < 35$ or $A_f \geq 65$)	1		
	($57 \leq A_f < 65$) or ($35 \leq A_f < 43$)	2	3	3
	($43 \leq A_f < 57$)	3		
Basin Shape Index (B_s)	$B_s \geq 4$	1		
	$3 \leq B_s < 4$	2	3	3
	$B_s \leq 3$	3		
Stream Length-Gradient Index (S_L)	$S_L > 600$	1		
	$300 < S_L \leq 600$	2	1	1
	$S_L < 300$	3		
S/N (Number of Class 1 indices)			2	2

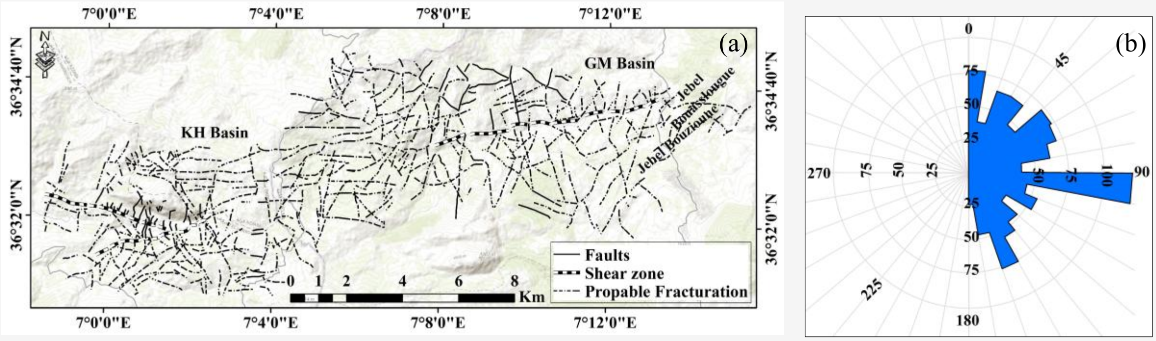

Figure 17: (a)Fracture mapping along the KH-ABF fault with orientation analysis using rose diagrams, and (b) orientation analysis using rose diagrams

3.3 Lineament Analysis

Remote sensing techniques, supported by analysis of aerial photographs, revealed a highly dissected landscape marked by significant tectonic activity [54]. Over 500 lineaments have been mapped within the KH-AB fault system and adjacent areas. The KH-AB fault is the main tectonic structure in the region, extending from the south-western limit of the Hammam El Meskoutine topographic sheet to its north-eastern extremity. Its course runs along the northern slopes of Jebel Bouasslougue and Jebel Bouzioune, underlining a clear structural control over the local topography (Figure 17(a)). Directional analysis using rosette diagrams revealed:

A dominant E-W orientation (90°-100°), probably corresponding to the oldest and most influential tectonic system, linked to the main dextral movement of the KH-AB fault.

A second, more recent, N-S (0°-10°) oriented fault system appears to segment the KH-AB fault into three morphologically distinct basins, reflecting a complex tectonic reorganization of the region (Figure 17(a)).

A third family of lineaments, oriented NW-SE (150°-160°), further complicates the structural fabric, probably contributing to localized zones of deformation (see rosette diagram Figure 17(b)).

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This structural configuration suggests polyphase tectonics, involving the probable reactivation of old faults under the effect of more recent stress regimes [55] and [56]. The structural complexity observed corroborates morphometric evidence of active tectonics and ongoing deformation.

4. Discussion

The Indice Relatif d'Activité Tectonique (IRAT - Relative Tectonic Activity Index) is a relevant tool for assessing neotectonic activity by integrating various geomorphological indicators. As defined by [4], this composite index is divided into four classes: Class 1 corresponds to very high tectonic activity (S/N = 1.0-1.5), Class 2 to high activity ($1.5 \leq S/N < 2.0$), Class 3 to moderate activity ($2.0 \leq S/N < 2.5$), and Class 4 to low tectonic activity ($S/N \geq 2.5$). In this study, the average IRAT value ($S/N = 2.0$) places the region in Class 3, indicating moderate tectonic activity (Tables 1 and 2). However, an in-depth analysis of morphometric parameters suggests that this classification may underestimate the tectonic reality of the area. The Basin Shape Index (B_s) for the Kef Hahouner fault (KHB) has a value of 1.43, reflecting a relatively rounded basin morphology. In conventional interpretation, such a value suggests little tectonic influence and more pronounced erosion [2] and [57].

However, field observations indicate that this rounded morphology may be linked to a dextral displacement along the Kef Hahouner-Aïn Berda (KH-AB) fault, rather than to prolonged erosion (Figure 18 (a)). In this context, the B_s index taken in isolation may therefore be misleading.

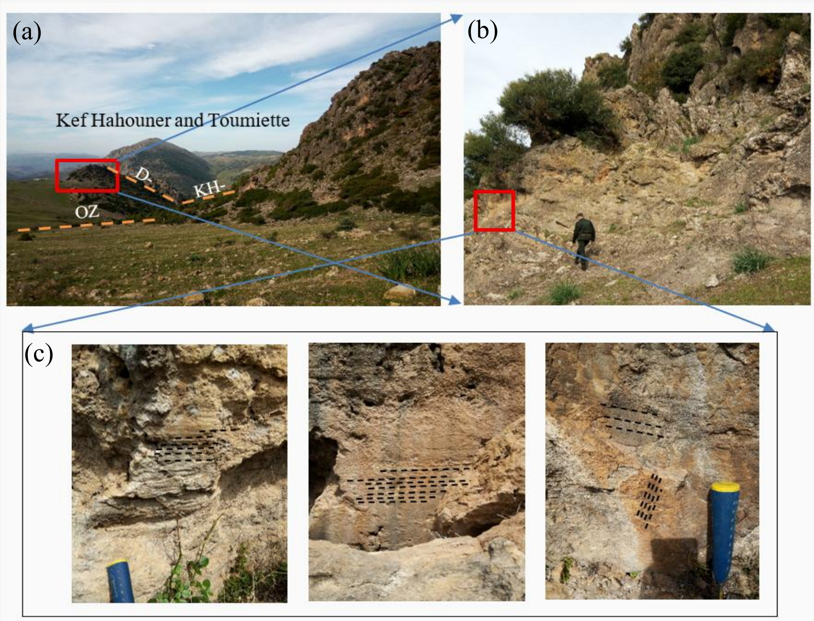

Figure 18: Structural framework and kinematic indicators of the major faults affecting the northeastern part of the Constantine Basin: (a) Panoramic view, (b) field view of the faulted carbonate outcrops, and (c) close-up views of fault planes

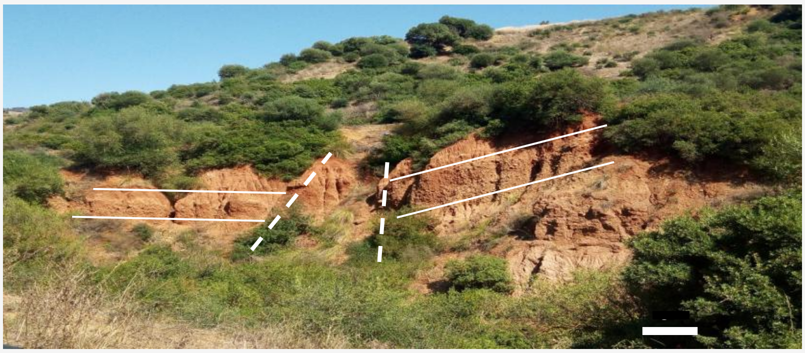

Figure 19: Quaternary terraces affected by active tectonics in the extension of the (KH-AB F) strike-slip fault

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D-HF – Dbar Hahouner Fault, OZF – Oued Zoubia N0° Sinistral Strike-Slip Fault, KH-AB F – Kef Hahouner–Ain Berda NE–SW Sinistral Strike-Slip Fault

Examination of other morphometric indicators also confirms the tectonically active nature of the region:

The Hypsometric Integral (Hi) for the KHB and GMB basins is 0.49, placing them in Class 2. This value reflects a transitional relief, neither totally young nor fully mature, typical of areas subject to active tectonic uplift and incipient erosion.

The valley width/height ratio (V_f) is less than 0.5 for both basins, revealing narrow V-shaped valleys, characteristic of active incision induced by recent tectonic uplift.

The stream length gradient index (S_L) exceeds 600 in both basins, placing them in Class 1. These high values reflect steep gradients associated with tectonic deformation, slope failures or lithological contrasts.

Asymmetry Factor (A_f) values of 53.54 for the KHB and 48.38 for the GMB place them in Class 3, indicating moderate tilting of the basins. Although these values do not indicate marked asymmetry, they could reflect recent lateral deformation rather than vertical uplift.

The Sinuosity of the Mountain Front (S_{mf}) for the KHB is 1.11, corresponding to Class 2. This suggests an actively retreating mountain front, typical of a tectonic escarpment undergoing rejuvenation.

Taking all these indices into account - notably the combination of high S_L, low V_f and moderate Hi - the tectonic setting appears to be more active than the initial IRAT classification suggests (Tables 1 and 2). Combined with field observations (displaced geomorphic surfaces, marked slope failures (Figure 18(b) and (c)) and seismic data, these analyses suggest that the region is closer to Class 2, reflecting high neotectonic activity (Figure 19).

5. Conclusion

This study presented an integrated morphostructural analysis of the Kef Hahouner–Djebel Debar (KHB) and Guendoula–Messigla (GMB) basins, located in the northeast of the Constantine basin. The approach adopted, combining morphometric indices, detailed extraction of lineaments from satellite and aerial images, and field observations, made it possible to accurately characterize recent tectonic activity in a complex intracratonic region. In particular, the KH–AB fault system was identified as a major structure controlling flow orientation, basin asymmetry, and relief dynamics. These results provide new insights into the morphostructural mechanisms shaping the Constantine basin and its surroundings.

The study highlights significant scientific contributions on two levels. On the one hand, from a methodological perspective, the integration of IRAT indices with high-resolution morphometric data provides a robust approach for identifying and classifying tectonic activity in regions with limited instrumentation. This method makes it possible to detect morphometric imbalances (S_L, V_f, S_{mf}, A_f, Hi, T) and link these anomalies to recent crustal movements, thus providing a valuable tool for morphotectonic assessment. Furthermore, in terms of new knowledge, the study reveals the recent reactivation of the morphotectonic corridor formed by the KH–AB system and associated structures, confirming the existence of persistent crustal stresses that modify the relief and influence the evolution of basins. These observations complement regional data on active tectonics, which are still poorly documented for the northeast of the Constantine Basin, and provide a better understanding of the structural dynamics of this area.

Nevertheless, certain limitations remain, notably the absence of precise geodetic data (GPS), temporal InSAR analyses, and high-resolution geophysical profiles for certain structures, such as the Oued Meheria Fault (OMF). These gaps restrict the precise quantification of vertical and horizontal displacements and limit the detailed modeling of tectonic stresses. Therefore, the results obtained should be considered a solid basis, but require further validation to refine the morphotectonic models and confirm the extent of the identified tectonic activity. For future research, it would be essential to integrate GPS and InSAR measurements, as well as detailed geophysical analyses, in order to quantify current deformation rates and better characterize the reactivation of deep structures. Combining these data with the morphometric tools already in use will make it possible to develop more accurate morphotectonic models and improve the mapping of areas at risk of seismicity and slope instability. In addition, the approach could be extended to other intracratonic basins in the Maghreb to compare morphostructural dynamics and assess regional variability in tectonic activity.

In summary, this research demonstrates the effectiveness of an approach combining morphometry, remote sensing, and field observations for the detection and evaluation of active tectonic structures. It provides new insights into the morphotectonics of the northeastern Constantine

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Basin, proposes a robust method for characterizing active tectonics in complex intracratonic contexts, and paves the way for future investigations integrating geodetic and geophysical data to refine the understanding of morphostructural processes and support land use planning and geological risk management in the region.

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