



Exploring neotectonic activity in a semiarid basin: a case study of the Ain Zerga watershed

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Abstract

Mediterranean basin exposed to ongoing processes of erosion and deformation. Neotectonics is the study of the geological processes involved in the deformation of the Earth's crust. The topography of the terrain is greatly impacted by these neotectonic events, which has a considerable impact on the drainage pattern and general geomorphology of the region. In this work, the active tectonics were evaluated using the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) and several Geomorphic Indices in the Ain Zerga region of Northeast Algeria. Asymmetry factor, basin form, the ratio of valley floor width to valley height, the sinuosity of mountain fronts, hypsometric integral, hypsometric curve, and transverse topographic symmetry factor were some of the indices used. These findings emphasize the tremendous tectonic activity that exists in the study area. In comparison to sub-watershed N°2, sub-watersheds N°1, N°3, and N°4 had stronger tectonic activity, according to the examination of these geomorphic indicators. The Relative Tectonic Activity Index (Iat) distribution pattern, which concurred with other pieces of information such as stream deflection and lineament analysis, corroborated these conclusions. We were able to learn a lot about the different levels of tectonic activity in the sub-watersheds by using traditional geomorphic indices. The tectonic activity-exhibiting basins consistently displayed connections with structural disturbances, basin geometry, and field research. Geomorphic indices and morphometric characteristics were used to identify tectonically active zones in a portion of the Mellegue transboundary basin, which shows a considerable influence of neotectonic activity in a portion of the Neogene basin.

Keywords Active faults · Erosion · Geomorphic indices · Sub-watersheds · Relief

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1 Introduction

Neogene basins are prone to deformational activities such as landslides, floods, and seismic events, [1–4]. In the Mediterranean basin's mountainous terrains, tectonic uplift, weathering, and denudational processes drive the evolution and modification of tectonically active regions [5]. These deformation processes have a direct impact on geomorphology, drainage patterns, and landform evolution. To understand past tectonic disturbances, geomorphological analysis of drainage networks provides valuable insights [6, 7]. Examining the drainage patterns enables us to unravel the active tectonic processes shaping landscape development within the geodynamic context. In the Medjerda Mellegue basin; neotectonic activities play a significant role in the occurrence of major disasters. Morphometric parameters and geomorphic indices serve as crucial tools for identifying and characterizing the deformational processes involved.

Tectonic geomorphology is an interdisciplinary field that has witnessed significant advancements in tools and techniques within the geosciences, encompassing geomorphological, geodetic, and geochronological methods. These methodologies provide invaluable insights into the processes that shape the Earth's surface, including uplift rates, incision rates, erosion rates, and slip rates on faults, operating across timescales ranging from thousands to millions of years [8–17]. It plays a key role in assessing natural hazards and facilitating land use development and management in populated areas [18–21]. By focusing on recent tectonic activity within a region and examining its influence on landforms, scholars can gain a deeper understanding of tectonic processes. This knowledge contributes to improved predictions of potential risks, as well as informs land-use planning and hazard mitigation strategies [22–26]. By analyzing the characteristics of tectonic landforms and the associated geological structures, researchers can identify regions prone to seismic events and other related hazards. This knowledge plays a significant role in urban planning and infrastructure development, minimizing potential risks and ensuring the safety of populations residing in tectonically active areas [27–29].

Furthermore, understanding the intricate interaction between tectonic activity and landforms contributes to the identification and characterization of geological processes that shape the Earth's surface. By integrating various geoscientific disciplines such as geology, geophysics, and stratigraphy, researchers gain deeper insights into the evolution of landscapes and the underlying mechanisms driving their formation [30–34]. The available evidence strongly supports the assertion that tectonic geomorphology offers a comprehensive framework for comprehending the dynamic

surface processes of the Earth. This field greatly enhances our understanding of land crust evolution by combining different geoscientific disciplines and employing diverse methodologies. Through unraveling the intricate relationship between tectonic activity and landforms, scientists are empowered to make invaluable contributions to enhance safety and promote sustainable development in tectonically active regions. In active tectonic regions, the influence of tectonic activity extends beyond crustal deformation and can significantly impact the drainage pattern of an area. Mechanisms such as basin asymmetry, stream deflection, and river incision are manifestations of this influence [35]. These geomorphic responses provide valuable evidence of ongoing tectonic processes and help elucidate the complex interactions between tectonics and landscape evolution. To quantify and characterize the effects of tectonic activity on landforms, geomorphic indices serve as invaluable tools. These indices, such as stream length-gradient, basin shape, and valley floor width-to-valley height ratio, enable the objective assessment of landscape morphology [36, 37]. By utilizing diverse data sources, including topographic maps, digital elevation models (DEMs), satellite images, aerial photographs, and field measurements, these indices can be computed and applied to various spatial scales and regions [38–41].

By integrating diverse geoscientific disciplines and utilizing geomorphic indices, researchers can quantitatively analyze the interactions between tectonic activity and landscape evolution. This interdisciplinary approach enables a comprehensive examination of tectonic processes, their impact on landforms, and the development of quantitative measures to assess and characterize tectonic activity in various regions.

The utilization of system-like regional modeling in the field of neotectonics in collapsed basins holds significant importance. These basins are characterized by complex geological and tectonic processes, and understanding their behavior and evolution is crucial for various applications, including hazard assessment and resource exploration. By employing a system-like regional modeling approach, researchers are able to capture the intricate interplay between different components of the system, such as fault networks, basin geometry, and stress distribution. This holistic perspective allows for a comprehensive analysis of the neotectonic processes, enabling the identification of key controlling factors and their spatial variations within the basin. Additionally, system-like regional modeling facilitates the integration of multi-disciplinary data, such as geological, geophysical, and geodetic information, providing a more robust and accurate representation of the basin's tectonic evolution. The insights gained from such modeling efforts can contribute to a better understanding of the basin's dynamics, assist in predicting future tectonic behavior, and guide decision-making processes related

to land-use planning and infrastructure development in these vulnerable regions. Overall, the use of system-like regional modeling in neotectonics offers a valuable tool for unraveling the complexities of collapsed basins and advancing our knowledge in this field.

We selected Ain Zerga as our case study due to its unique geological setting, positioned between two distinctive domains. Additionally, its geological history has been significantly influenced by diapiric Triassic extrusion, contributing to its geological complexity and interest for investigation. Moreover, the region is bordered by important collapsed basins, presenting a compelling opportunity to explore and understand the neotectonic processes that have shaped the landscape [42–45].

Our research aims to assess the behavior of the most-easterly slumping basins in Algeria. To achieve this, we employ various geomorphic indices and conduct a detailed analysis of drainage shapes. Our study is structured around three key steps to accomplish our research objectives:

(a) Extracting the drainage network and deriving geomorphic indices using digital and topographic data. (b) Preparing, rescaling, and geoprocessing these indices within a GIS platform. (c) Combining the seven dependent variables to calculate the Iat index.

This study demonstrates the significance of investigating morphotectonic features to track the neotectonic activity of collapsed basins in North Africa and similar geological structures.

The findings not only contribute to the assessment of seismic hazard potential in the region but also enhance our understanding of the geological processes that influence tectonic activity.

2 General setting

The research region is situated near the Algerian-Tunisian border, on the northernmost tip of the Saharan Atlas mountain range [46]. Its geographic location lies between

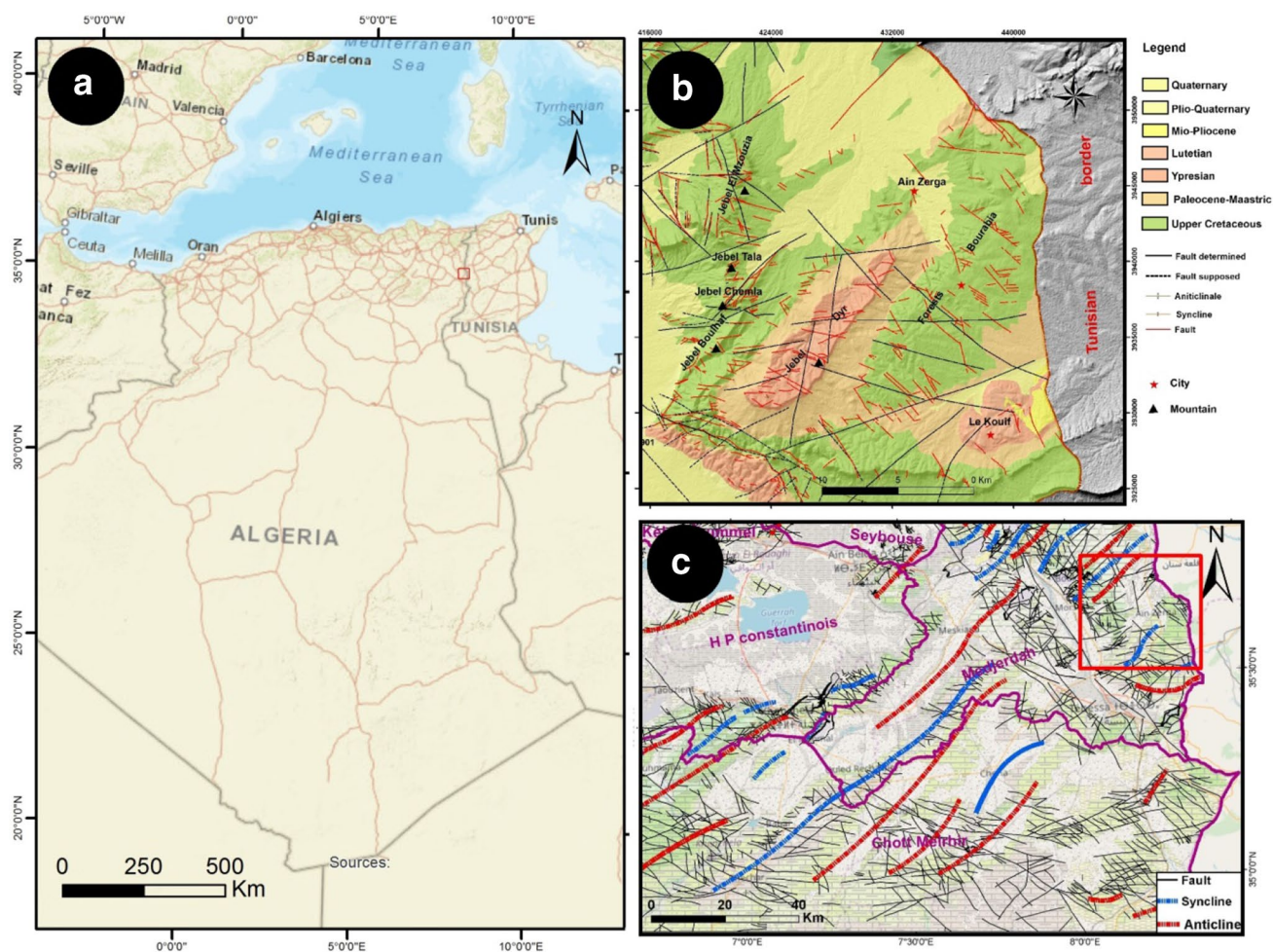


Fig. 1 a Geographic location of the study area; b stratigraphic simplified map of the study area; c structural scheme of the study area

35°30'N and 35°40'N latitude and 08°07' to 08°20'E longitude (Fig. 1a). It is located around 50 km from the province of Tebessa's capital. Jebel Dyr, a syncline distinguished by Cenozoic rock formations, is a notable geological feature in the region [47]. The study region is primarily composed of carbonate formations, resulting in the development of synclines and anticlines. Notably, Ypresian limestones have contributed to the formation of shelters in the area [48–50]. The stratigraphic sequence is characterized by alternating layers of limestones, marly-limestones, and argillaceous marls formations [51, 52]. In the central parts of the basin, Plio-Quaternary terrains are present, encompassing diverse features such as alluvial fans, silts, calcareous crust, conglomerates, and gravels (Fig. 1b) [53].

The study area is bordered by two major faults with an orientation of NW–SE. Analysis of lineaments reveals three primary fault sets: NW–SE, NE–SW, and E–W, with the NW–SE, set being the most prominent in the study area. The distribution of the NW–SE and NE–SW fault sets shows a relatively consistent pattern [54–56]. Lineament and gravimetric analyses provide evidence supporting the tectonic origin of the grabens and the presence of Quaternary deposits covering significant tectonic faults [57, 58]. Gravimetry further confirms the existence of significant NW–SE, and NNW–SSE faults between Morsott and Jebel Ezzitouna (Fig. 1c), [59, 60]. The study area experiences a semi-arid climate with an annual precipitation of less than 400 mm [61]. Aquiferous formations in the area include the Maestrichtian limestone aquifer, the shallow Plio-Quaternary aquifer, and the Eocene limestone aquifer.

3 Material, methods and data acquisition

To fully analyze the research region, we used a variety of data-gathering methodologies in this study. First, we used a high-resolution, 30-m-resolution-meter-resolution digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM). We also included the topographic and geological maps from Meskiana (N°177) and Morsott (N°178). To complement these datasets, we conducted field measurements to acquire primary data. From the DEM data, we extracted morphometric indices and delineated the basins within the study area. The study area was divided into four catchments to facilitate our analysis. Geomorphic indices were then applied to evaluate and assess the relative tectonics at play. Specifically, we calculated the Iat index, which encompasses the hypsometric integral (HI), mountain front sinuosity (Smf), basin asymmetry factor (Af), basin shape index (Bs), transverse topographic symmetry factor (T), stream-length gradient (SL) [62]. These indices were carefully chosen to capture various landscape characteristics and their response to tectonic processes. For data analysis and

layer digitization, we utilized Xlstat-Pro and ESRI-ArcGIS software. Statistical analyses were conducted, allowing us to evaluate various morphometric parameters within the study area. A Geographic Information System (GIS) program was used to rasterize, process, and analyze the obtained theme data. We were able to fully comprehend the relative rates of active tectonic activities in the studied area by using these morphometric studies and merging the calculated indices. The hypsometric integral provided insights into elevation distribution and potential uplift history, while the stream-length gradient revealed patterns of river network steepness and incision. Understanding the impact of tectonic forces on landscape asymmetry and locating fault-related structures were made easier with the help of the transverse topographic symmetry factor. The basins' overall shape, geometry, and deformation patterns were also revealed by the basin asymmetry factor, basin shape index, valley floor width to valley height ratio, and mountain front sinuosity. These indices worked together to provide a thorough evaluation of the ongoing tectonic processes influencing the research area.

3.1 Geomorphic indices

3.1.1 Stream length gradient index (SL)

The stream-length (SL) index serves as a valuable measure to assess the relative activity of tectonic movements within a region. It aids in identifying deviations from a stable river profile, which can result from a variety of factors such as lithological, climatic, and tectonic influences. High SL values associated with soft rocks suggest a recent tectonic activity, while low SL values may indicate the presence of active strike-slip faults [63]. The persistent resistance displayed by the rocks in the area further indicates ongoing tectonic activity. Fluctuations in the stream length index or the gradient of SL values also provide evidence of tectonic activity within the area [64]. The SL values can be categorized into three classes: values over 500 belong to the first class, values between 300 and 500 belong to the second class, and values below 300 belong to the third class [65]. The SL index is calculated using (Eq. 1):

$$SL = (\Delta H)/(\Delta L)/L \quad (1)$$

where $\Delta H/\Delta L$ represents the slope gradient of the main watercourse segment and L denotes the total length between the upstream and the midpoint of the watercourse segment.

3.1.2 Ratio of valley floor width to valley height (Vf)

The valley floor width to valley height ratio (Vf) index serves as an indicator of the disparity between down-sloping and elevated valleys, which is influenced by active uplift

processes (resulting in low Vf values). Valleys with high Vf values experience erosion as broad-floored valleys carve into adjacent hill slopes. Additionally, these valleys are influenced by the stability of the base level [66].

A deep V-shaped valley ($V_f < 1$) is associated with a network of linear downcutting streams, characteristic of areas that have undergone active uplift. Conversely, flat-floored valleys ($V_f > 1$) are generally subject to erosion, primarily driven by relative tectonic quiescence. Different classification values for the Vf index have been proposed by researchers [65].

3.1.3 Hypsometric curve and hypsometric integral (HI)

The hypsometric curve represents the relationship between altitude and area in a landscape. The hypsometric integral (HI) is a metric used to characterize the distribution of elevations within a drainage basin and is particularly informative about tectonic behavior and erosional stages [67–70]. Concave-up hypsometric curves with high HI values indicate a youthful stage, while S-shaped curves crossing the center represent a mature stage. Conversely, concave curves with low HI values signify an old stage [71]. There are three classes of hypsometric integrals: class 1 ($HI > 0.5$) for convex hypsometric curves, class 2 ($0.4 < HI < 0.5$) for straight or concavo-convex curves, and class 3 ($HI < 0.4$) for concave curves. Convex hypsometric curves are associated with high HI values, while concave curves indicate lower values. Low-lying areas may be linked to uplift from faults or recent folding events.

3.1.4 Mountain front sinuosity (Smf)

The computation of Smf values can also be done using satellite imagery or aerial photography, with the obtained value depending on the scale of the map. While a small-scale map provides an approximate Smf value, a large-scale aerial photography or topographic map with higher resolution can offer a more accurate assessment. The SMF index serves as a quantitative measure to evaluate the contributions of tectonic uplift and erosion to the topography of a mountain front. This index is based on the observation that tectonically active areas typically exhibit relatively straight mountain fronts, whereas areas with high erosion rates tend to have irregular or sinuous mountain fronts [72]. According to Bull and McFadden, [73], the Smf value is defined as follows:

$$Smf = Lmf/Ls \quad (2)$$

Here Lmf represents the length of the mountain front along the mountain-piedmont junction, and Ls refers to the straight-line length of the mountain front [74]. A Smf value close to 1.0 indicates a relatively straight mountain front,

suggesting significant tectonic activity. In such cases, the mountain range has likely experienced notable uplift and deformation due to tectonic forces, resulting in a linear mountain front. Conversely, higher Smf values (> 3.0) indicate that the mountain front has been shaped by erosion and is relatively tectonically quiescent.

3.1.5 Asymmetry factor (AF)

The Asymmetry Factor (AF) is utilized as a measure to identify tectonic tilting in a catchment area on a regional scale. Its initial definition was provided by Hare and Gardner [75] and Pérez-Peña et al. [76]. The formula for calculating AF is as follows:

$$AF = 100(A_r/A_t) \quad (3)$$

where A_r represents the catchment area to the right of the main trunk stream, and A_t represents the total drainage area of the entire catchment. A value of 50 indicates no tilting in the catchment, while higher or lower AF values indicate tilting of the area. The deviation from the measured AF value to the neutral value of 50 is referred to as AF-50.

For the evaluation of IRTA, asymmetry classes based on AF-50 values have been defined by Giaconia et al. [77], and Selçuk [78]. These classes are as follows:

- Symmetric: $AF-50 < 5$, indicating little or no tilting.
- Gently asymmetric: $AF-50$ between 5 and 10, indicating a slight degree of tilting.
- Moderately asymmetric: $AF-50$ between 10 and 15, indicating a moderate degree of tilting.
- Strongly asymmetric: $AF-50 > 15$, indicating a strong degree of tilting.

3.1.6 Drainage basin shape index (Bs)

The Drainage Basin Shape Index (Bs) is a metric used to assess the elongation of a river basin. It is calculated by dividing the length of the basin by its maximum width at the widest point. The formula to compute Bs is as follows:

$$Bs = B_l/B_w \quad (4)$$

where B_l represents the length of the basin, measured from the furthest point upstream to the outlet, and B_w is the maximum width of the basin, measured perpendicular to the main channel at its widest point.

River basins often exhibit elongated shapes due to their formation through active tectonic processes like faulting, folding, and uplift. The Bs index is commonly employed to quantify the degree of elongation of a river basin, with higher values indicating a more elongated shape. In the given statement, the Bs values have been categorized into

three main intervals or classes based on their magnitude. Class N°1 corresponds to the most elongated basins, with a Bs value greater than 2.9. Class N°3 represents the least elongated basins, with a Bs value less than 1.9. Class N°2 encompasses basins with intermediate elongation, having Bs values between 1.9 and 2.9. This classification scheme aids in understanding the characteristics and behavior of different river basins based on their shape. For instance, highly elongated basins with a Bs value above 2.9 might be more susceptible to flash floods and debris flows due to their steep slopes and rapid runoff. Conversely, less elongated basins with a Bs value below 1.9 may exhibit more stable hydrological patterns and lower erosion potential.

3.1.7 Transverse topographic symmetry factor (T)

The Transverse Topographic Symmetry Factor (T) is a metric used to assess the asymmetry of a valley cross-section and is commonly employed in geomorphology to study river valleys and other landforms. The T-factor index is calculated by dividing the difference between the two sides of the valley cross-section by their sum. Specifically, it is the difference between the areas of the two halves of the cross-section divided by the total area of the cross-section. The T-value of zero indicates perfect symmetry, while values greater than zero indicate increasing asymmetry towards one side of the valley cross-section. A T-value of 1 indicates that all of the areas are located on one side of the cross-section [79]. An alternative formula to calculate the T-factor index is:

$$T = Da/Dd \quad (5)$$

where Da represents the distance from the midline of the drainage basin to the meander belt, and Dd is the distance from the basin midline to the basin divide.

The T-factor is a valuable tool for understanding how geomorphic processes such as erosion and sedimentation have shaped a valley and can provide insights into its potential future changes.

4 Result and discussion

4.1 Morphometric indices

The following findings are presented in Table 1, which provides a comprehensive summary of the calculated numerical values for the morphometric indices and the hydrographic networks across all Sub-Watersheds:

Morphometric Indices: The table showcases the results of the calculation process for various morphometric factors, shedding light on the quantitative measurements associated with the shape, size, and relief characteristics of each Sub-Watershed. These indices serve as valuable indicators for assessing the geomorphological characteristics and hydrological behavior of the studied area.

Hydrographic Network: Additionally, the table presents the outcomes of the analysis conducted on the hydrographic network within the Sub-Watersheds. This analysis involves quantifying the network's attributes. These parameters play a crucial role in understanding the drainage patterns and the overall hydrological connectivity of the Sub-Watersheds.

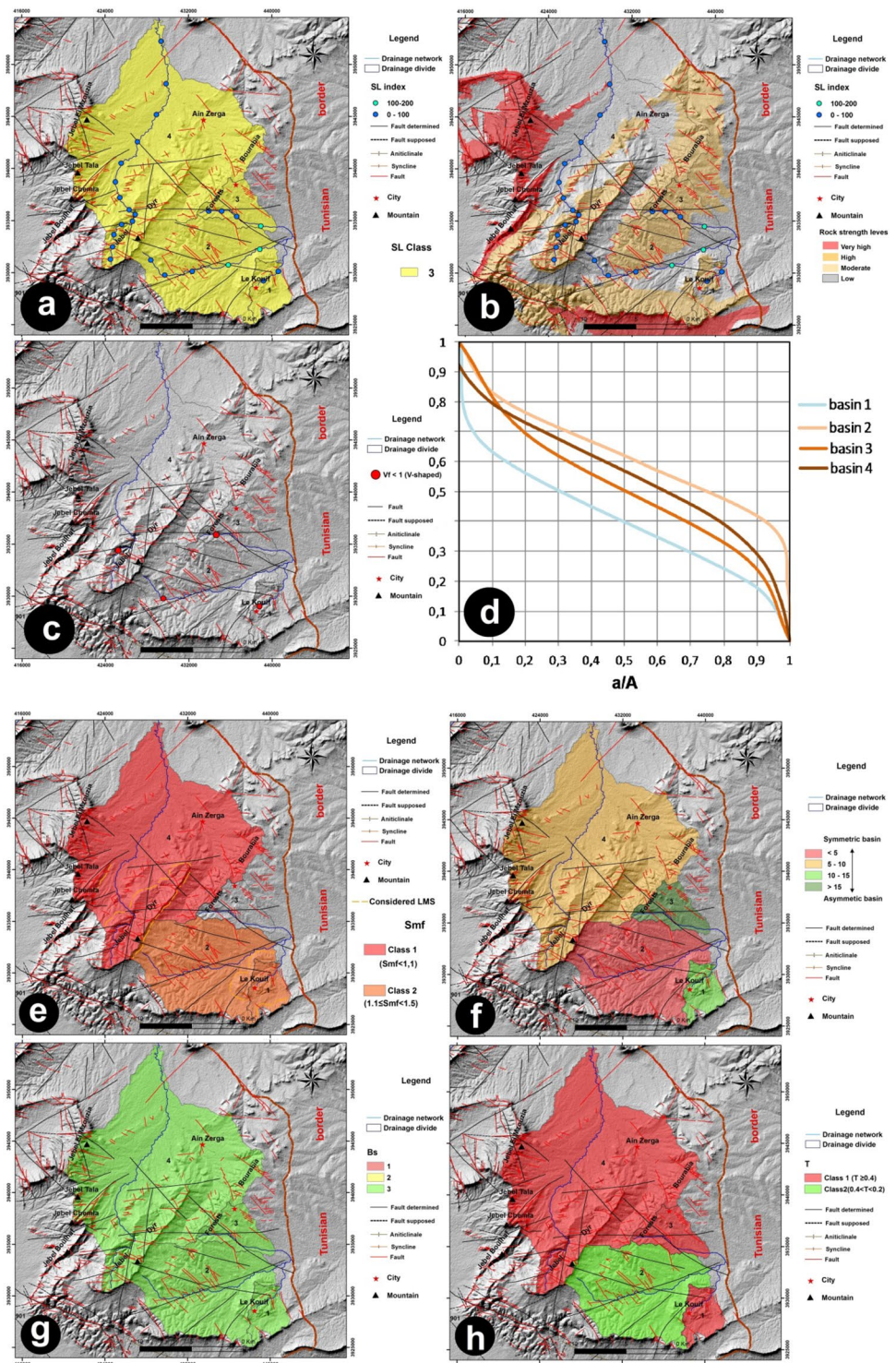
By consolidating these results in Table 1, it becomes easier to observe and compare the morphometric indices and hydrographic network characteristics across the different Sub-Watersheds, facilitating a comprehensive understanding of their spatial variations and interrelationships.

The analysis of the Stream Length Gradient Index (SL) reveals significant insights into the characteristics of the study area's hydrographic network. The results demonstrate a diverse range of SL values, spanning from 13.9 in basin N°4 to 91.28 in basin N°2, indicating substantial variations in stream length gradients among different sub-watersheds. When examining the distribution of SL values, it becomes evident that the majority of the study area falls within class 3, as illustrated in Fig. 2a. This suggests a relatively moderate slope gradient throughout the sub-watersheds, indicative of a balanced hydrological network. Interestingly, the observed changes in SL values appear to be primarily influenced by structural zones rather than lithological variations, as depicted in Fig. 2b. This highlights the dominant role of structural characteristics, such as fault lines or tectonic activities, in shaping the stream length gradients within the study area. These findings emphasize the significance of considering structural elements when analyzing the hydrographic

Table 1 Morphometric indices values for all sub-watersheds

| Basin | HI | AF | AF-50 | BS | Mean SMF | Mean SL | Mean T | Vf |
|-------|------|-------|---------|------|----------|---------|--------|------|
| N°1 | 0.5 | 63.79 | 13.79 | 1.58 | 1.1 | 59.15 | 0.6 | 2.15 |
| N°2 | 0.5 | 52.48 | 2.48 | 1.5 | 1.15 | 91.28 | 0.29 | 4.16 |
| N°3 | 0.5 | 78.49 | 28.49 | 1.26 | / | 68.25 | 0.59 | 4.7 |
| N°4 | 0.48 | 39.96 | – 10.04 | 1.34 | 1.09 | 13.9 | 0.41 | 5.71 |

Fig. 2 **a** SL index class distribution map; **b** the rock resistance and SL map; **c** distribution map of the morphology index of (Vf); **d** hypsometric curves; **e** Mountain front sinuosity index map; **f** geomorphometric asymmetry index distribution map; **g** BS index distribution map; **h** T-index classes map



network, as they can have a pronounced impact on the overall stream morphology and hydrological behavior. By unraveling the relationship between SL values and structural zones, a deeper understanding of the spatial patterns and geological influences on the stream network can be attained.

The assessment of the Ratio of Valley Floor Width to Valley Height (V_f) provides valuable insights into the

characteristics of the sub-watersheds master streams. The computation of V_f values was performed, following the methodology outlined by El Hamdouni et al. [65], using the master stream data. In our study area, the V_f index is classified into two distinct classes: class 1 ($V_f < 1$) and class 2 ($V_f > 1$). The analysis reveals that the average V_f value for the sub-watersheds in our study area surpasses one,

indicating that they fall into class 2, as depicted in Fig. 2c. This finding implies the presence of flat-floored valleys throughout the study area. The prevalence of class 2 Vf values suggests a notable contrast between the width of the valley floor and its corresponding height. The relatively higher Vf values signify that the valleys within the sub-watersheds exhibit wider floor areas concerning to their overall height, indicating the existence of expansive and relatively level valley floors. Understanding the distribution and characteristics of Vf values contributes to our comprehension of the sub-watersheds' geomorphology and landscape dynamics. The presence of flat-floored valleys can have implications for land use, drainage patterns, and hydrological processes within the study area, underscoring the importance of further investigation and analysis in these aspects.

The hypsometric curve and hypsometric integral (HI) serve as valuable tools for understanding the geological evolution and tectonic activity within a region. The HI index encompasses values derived from diverse active tectonic regions. Typically, higher HI values indicate more recent tectonic activity, while lower values are indicative of older landscapes that have experienced considerable erosion over time. In our study area, the analysis of the hypsometric curves revealed high to moderate HI values, closely approaching 0.5, across the four sub-watersheds. These values indicate a relatively balanced equilibrium between erosion and uplift processes. The shapes of the HI curves for the sub-watersheds exhibit a predominantly convex to sub-rectilinear pattern, as illustrated in Fig. 2d. The hypsometric curves and their corresponding HI values provide valuable insights into the erosional history and geomorphological characteristics of the study area. By examining the shape and magnitude of the HI curves, it becomes possible to estimate erosion rates along the valleys within the sub-watersheds. This information is crucial for understanding the dynamics of landscape evolution, erosion patterns, and the impact of tectonic forces on the shaping of the terrain.

Mountain front sinuosity (Smf) serves as an important indicator of tectonic activity and the erosional history of a mountainous region. The process of prolonged erosion has likely contributed to the smoothing out of irregularities along the mountain front, resulting in a more sinuous or irregular appearance that may no longer accurately reflect underlying tectonic activity (17). Within our study, the assessment of mountain-front sinuosity reveals a range of Smf values from 1.09 to 1.15 across the analyzed area. These values signify a tectonically active zone, as depicted in Fig. 2e. The relatively higher Smf values indicate a greater degree of irregularity and sinuosity along the mountain front, suggesting ongoing tectonic processes that have influenced the shaping and erosion of the landscape. The analysis of Smf values provides valuable insights into the dynamic nature of the study area's geology and geomorphology. The presence

of a tectonically active zone is indicative of ongoing crustal deformation and the potential for seismic activity.

The Asymmetry Factor (AF) is a significant parameter that allows us to assess the degree of asymmetry in catchment shapes. By analyzing AF values, we can gain insights into the spatial characteristics and geological processes that have shaped the catchments within our study area. In our analysis, the average AF values range from 27 to 86 across the catchments. It is noteworthy that catchments 4 and 2 exhibit relatively symmetrical shapes, suggesting a balanced erosion pattern and uniformity in their drainage networks. This symmetry is reflected in the lower AF values associated with these catchments. On the other hand, catchments 1 and 3 exhibit the highest asymmetry values, indicating pronounced irregularities in their shapes and drainage patterns. These catchments deviate significantly from symmetrical forms, suggesting the influence of specific geomorphic processes or geological factors that have caused their asymmetry. The observations of catchment asymmetry provide valuable information about the underlying geological and geomorphological processes at work within the study area. The presence of high asymmetry values in catchments 1 and 3 may indicate the influence of geological structures, such as faults or lithological variations, which have impacted the erosion and shaping of these catchments. By considering the AF values alongside other morphometric indices and geological data, we can gain a more comprehensive understanding of the catchment characteristics, landscape evolution, and the interplay between geological processes and drainage patterns.

The Drainage Basin Shape Index (Bs) is a valuable metric used to evaluate the shape characteristics of catchments within a study area. From the information provided, it is evident that your research involves comparing Bs values across different catchments, which range from 1.26 in basin N°3 to 1.58 in basin N°1. The analysis reveals that the majority of the study area's catchments fall into the third class, as depicted in Fig. 2g. This class signifies nearly circular shapes for these catchments. The Bs values provide insights into the overall roundness or elongation of the catchments, allowing for a comprehensive assessment of their geometric properties. The variations in Bs values highlight the diversity in catchment shapes within the study area. Basin N°1 exhibits the highest Bs value, suggesting a relatively elongated or elongated shape. In contrast, basin N°3 has the lowest Bs value, indicating a more circular or rounded shape. These findings contribute to a better understanding of the morphological characteristics of the catchments and their hydrological behavior. The analysis of Bs values assists in delineating the spatial patterns of catchment shapes and identifying potential influences such as underlying geological structures or erosional processes. By examining Bs values alongside other morphometric indices and geological

data, it is possible to gain deeper insights into the relationship between catchment shape, hydrological processes, and the underlying geomorphological factors.

The Transverse Topographic Symmetry Factor (T) is a valuable parameter used to assess the symmetry of valleys within sub-watersheds. Based on our analysis results, the T -values have been categorized into three classes according to their magnitude: class 1 for $T > 0.4$, class 2 for $0.2 < T < 0.4$, and class 3 for $T < 0.2$. These classes serve as indicators of different levels of symmetry observed in the valleys of the sub-watersheds. Higher T -values, corresponding to class 1, suggest a greater degree of symmetry in the valleys. On the other hand, lower T -values, falling into class 2, indicate a relatively lower level of symmetry. The analysis of the sub-watersheds in the study area reveals varying degrees of valley symmetry. Some sub-watersheds exhibit high levels of symmetry (class 1), while others display lower levels of symmetry (class 2), as illustrated in Fig. 2h. This suggests the presence of distinct valley patterns and asymmetry across the study area. The findings highlight the importance of considering valley symmetry when assessing the geomorphological characteristics and hydrological behavior of the sub-watersheds. Valley symmetry can provide insights into the underlying geological processes, such as tectonic activities or erosional patterns that have influenced the formation and development of the valleys. By examining T -values in conjunction with other morphometric indices and geological data, a more comprehensive understanding of the spatial distribution and significance of valley symmetry can be obtained.

4.2 Discussion

The scientific method of morphometric analysis involves assessing and analyzing the physical properties of the Earth's surface, such as its shape, slopes, and drainage systems. Researchers can learn a lot about the tectonic processes that have created the terrain over time by examining these structures. Morphometric analysis has produced important information about the tectonic activity in the research area, specifically within the context that has been supplied. The examination of the morpho-structural scheme has identified the presence of Atlasic structures, which are tectonic features commonly observed in the Atlas Mountains of North Africa. These structures exhibit extensive folding and faulting, believed to have occurred during the Mesozoic era. Notably, the east–west orientation of these structures suggests their formation as a result of compressional forces acting from the east and west.

Furthermore, the analysis of the map has unveiled the existence of glacis and their associated structural positions, as well as the presence of excreta cones and their multiple generations. These findings provide insights into the

movement of the masses, the orientation of their development, and their respective shapes and positions. Importantly, the research confirms that tectonic manifestations during the Plio-Quaternary period have been strongly influenced by geological faults inherited from a previous tectonic phase, occurring during the Cretaceous period (Fig. 3).

The comprehensive morphometric analysis conducted in this study enhances our understanding of the study area's geological history and the underlying tectonic forces that have shaped its landscape. By combining quantitative measurements and spatial analysis, researchers can draw meaningful conclusions about the processes and events that have contributed to the current geological features. These findings contribute to broader scientific knowledge, geological mapping efforts, and improved interpretations of regional tectonic dynamics.

4.3 Iat calculation

Utilizing a variety of geomorphic and drainage indices, the Relative Tectonic Activity Index (Iat) is a statistic used to assess the degree of tectonic activity within a particular location. In this study, the Geographic Information Framework Data (GIFD) approach was used to calculate the Iat index for four sub-basins. The hypsometric integral (HI), asymmetry factor (AF), stream-gradient index (SL), valley floor width to valley height ratio (Vf), basin shape ratio (Bs), transverse topographic symmetry factor (T), and mountain front sinuosity (S_{mf}) are the seven different parameters that make up the index (Table 2).

The analysis has brought to light various anomalies in the drainage system, mountain fronts, and valley slopes, which have been quantified utilizing morphometric indices such as the Valley Floor (VF) and Hypsometric Integral (HI) index. Additionally, the deviation of the hydrographic network from the T index has been assessed. Moreover, the distribution of relative tectonic activity has been examined through the active tectonic index (Iat).

The Iat index has been computed as the average of the seven morphometric indices: Vf, S_{mf}, SL, Af, Bs, HI, and T . Subsequently, the index has been categorized into four primary classes representing different levels of tectonic activity: extremely high tectonic activity ($IAT < 1.5$), high tectonic activity ($1.5 < IAT < 2$), moderate tectonic activity ($2 < IAT < 2.5$), and low tectonic activity ($IAT > 2.5$). The distribution of IAT values across the study area is depicted in the provided map (Fig. 4). The map highlights the presence of high and moderate Iat values throughout the basins, while low Iat values are only observed in sub-basin N°2.

The Iat index's assessment of relative tectonic activity serves to shed important light on the research area's dynamic nature. Researchers can fully comprehend the tectonic processes and their spatial distribution by taking a variety of

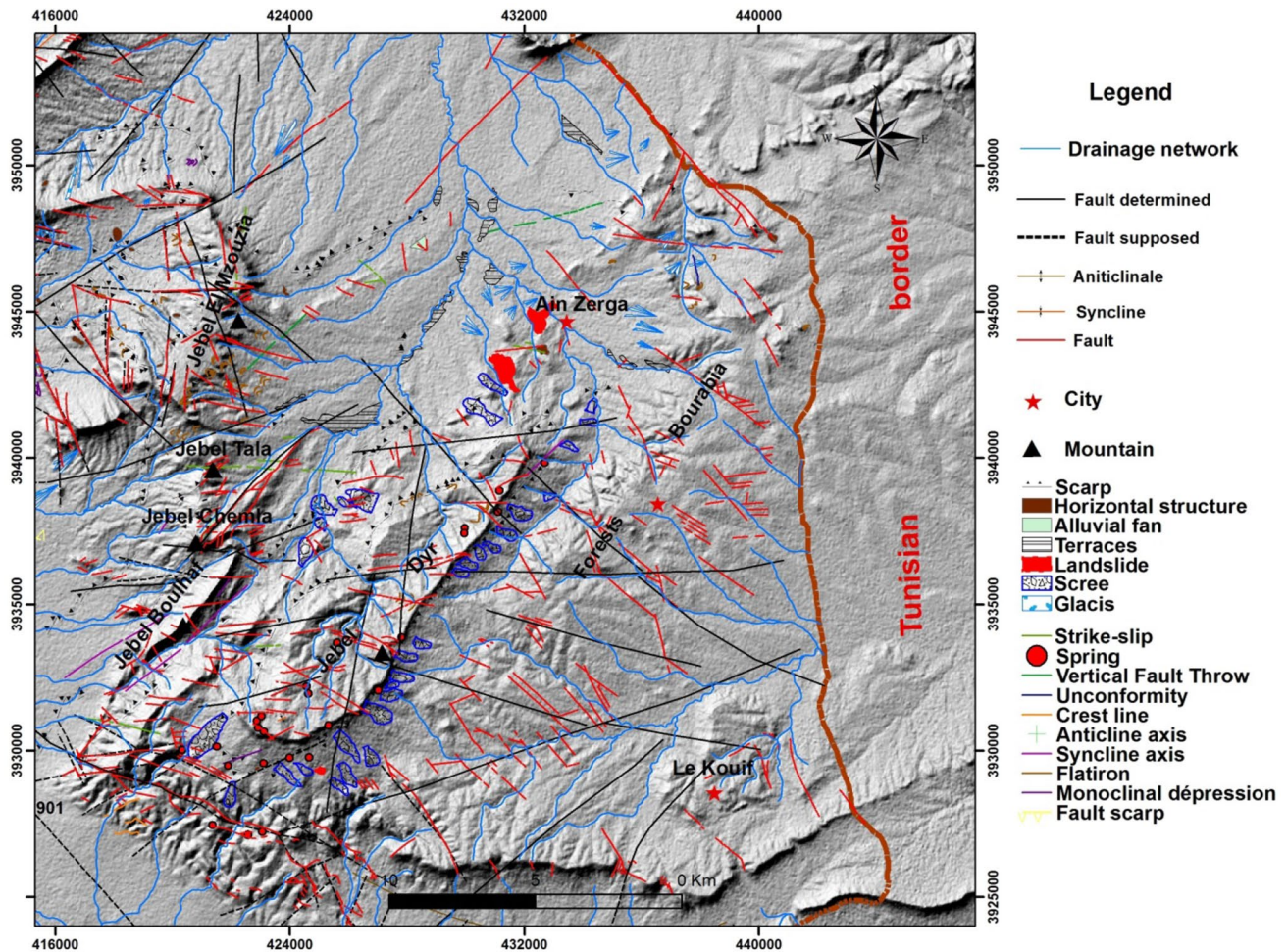


Fig. 3 Morpho-structural map of the study area

Table 2 Iat classification

| Basin | SL | BS | AF | HI | VF | T | SMF | S/n | Iat class | Assessen |
|-------|----|----|----|----|----|---|-----|------|-----------|------------|
| N°1 | 3 | 3 | 2 | 2 | 3 | 1 | 2 | 2.28 | 3 | Moderately |
| N°2 | 3 | 3 | 3 | 2 | 3 | 2 | 2 | 2.57 | 4 | Low |
| N°3 | 3 | 3 | 1 | 2 | 3 | 1 | / | 2.16 | 3 | Moderately |
| N°4 | 3 | 3 | 2 | 2 | 3 | 1 | / | 2.00 | 2 | High |

morphometric characteristics into account. These discoveries help to advance our understanding of local tectonic activity and to inform future geological research, risk evaluations, and land management decisions.

5 Conclusion

The northern portion of Jebel Dyr demonstrates notably high levels of activity, according to the examination of the area using RIAT values, with about one-third of it showing signs of moderate to high tectonic activity. Given that faults and

folds can affect rock properties, which may be reflected in these data, the study most likely used measurements like HI and Bs to evaluate the geological attributes.

Notable indicators of highly active class 2 tectonic activities include the presence of prominent tectonic faults, abrupt changes in stream direction, significant fractures, sudden river meandering, and straight mountain fronts. The obtained Vf value suggests a high rate of incision associated with increased erosion rates. These results underscore the effectiveness of the RIAT calculation method, utilizing geomorphic indices, for evaluating tectonic activity. Geomorphic indices serve as quantitative measures of landscape

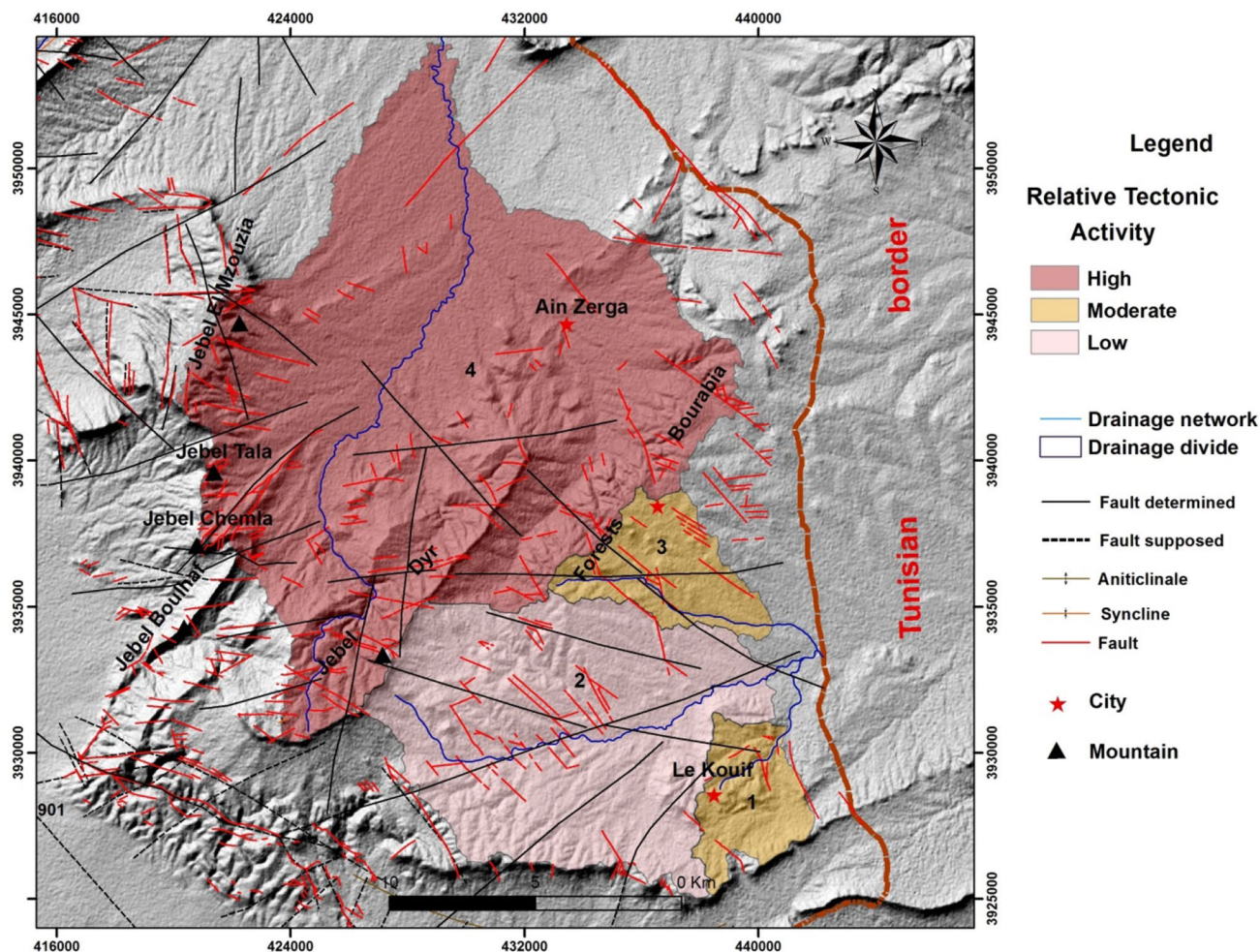


Fig. 4 Tectonic activity index (Iat) map of the study area

shape and form, providing valuable insights into the presence and magnitude of tectonic activity. A notable discovery is the validation of the Iat calculation using geomorphic indices, which shows the method's potential for determining tectonic activity in other regions. Understanding an area's geological properties and assessing the dangers involved with human activities like construction, infrastructure development, or resource extraction require this information. To enhance the understanding of tectonic activity in the area, it is recommended to conduct additional field investigations and geological surveys. This should include detailed fault mapping, rock deformation measurements, and identification of other geomorphic features related to tectonic activity. Establishing monitoring networks for continuous tracking of ground deformation, seismic activity, and landscape changes is essential for better assessing tectonic processes and identifying potential hazards and risks. Comparative studies with similar geological regions can provide valuable insights into regional variations of tectonic activity, contributing to a broader understanding of underlying mechanisms and

their implications. These studies play a crucial role in hazard assessment and risk management, aiding in the identification of areas prone to seismic events and other geological hazards. Furthermore, they inform urban planning, infrastructure development, and land-use regulations to minimize risks. The assessment of tectonic activity and its implications also guides environmental impact studies, facilitating the adoption of sustainable practices and mitigation measures for projects involving construction, mining, or resource extraction. Sharing data, methodologies, and research findings with other researchers in the field promotes scientific collaboration, standardized approaches, and an improved understanding of tectonic processes on a broader scale.

In conclusion, this research report emphasizes the significance of employing morphometric indices to study tectonic activity. To increase our knowledge of tectonic processes and their effects on the environment and human activities, the recommendations and outlook perspectives emphasize the need for additional research, monitoring initiatives, and collaboration.

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Author contributions HT conducted fieldwork and manuscript preparation; Prof. RH and YH reviewed and edited the manuscript, provided supervision and validation of the work; MSB and SA assisted with data processing and numerical modeling.

Data availability All data and materials presented in this manuscript are available and accessible.

Declarations

Conflict of interest The authors confirm that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper. The authors also state that no funding was received for this study.

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