Geology, Terrain Morphometry, and Environmental Patterns of the Belezma–Batna Anticline (Northeastern Algeria): An Integrated Remote Sensing and GIS Analysis

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Abstract

The Belezma–Batna anticline, located within the Pre-Atlasic domain of northeastern Algeria, represents a structurally controlled mountain system characterized by pronounced relief, complex drainage organization, and heterogeneous vegetation cover. This study applies an integrated geomorphometric and remote sensing approach to investigate the relationships between geological structure, terrain morphology, hydrological organization, and vegetation distribution within the massif. Digital elevation data derived from the Shuttle Radar Topography Mission (SRTM) and multispectral Sentinel-2 imagery were processed using Google Earth Engine and GIS techniques. Terrain morphometric parameters, including slope, Topographic Position Index (TPI), terrain curvature, and Relative Elevation Index (REI), were derived from the DEM, while drainage organization was evaluated using HydroSHEDS flow accumulation data and drainage density analysis. Vegetation patterns were assessed using the Normalized Difference Vegetation Index (NDVI).

The results reveal a strongly structured mountainous landscape dominated by an elongated ENE–WSW ridge system corresponding to the axis of the Belezma–Batna anticline. Slope values range from 0° to 43.84° with a mean of 6.84°, highlighting pronounced topographic contrasts between the central ridge and surrounding piedmont areas. Morphometric analyses demonstrate that resistant carbonate formations form elevated ridge systems, whereas weaker marl-rich and siliciclastic units preferentially occupy valleys and structural depressions. Drainage analysis indicates a predominantly dendritic to sub-dendritic network strongly influenced by ridge–valley morphology and structural orientation. A weak negative correlation between slope and drainage density ($r = -0.208$) suggests that drainage development is controlled by multiple interacting factors, including lithology, structure, and hydrological conditions. NDVI values reveal clear spatial relationships between vegetation distribution, topography, and environmental gradients, with dense vegetation concentrated in mountainous sectors and lower vegetation cover characterizing peripheral plains.

The integrated results demonstrate that the geomorphology of the Belezma–Batna anticline is governed by the interaction of tectonic structure, lithological resistance, fluvial erosion, and eco-hydrological processes. The study highlights the effectiveness of combining geomorphometric analysis and satellite remote sensing for investigating structurally controlled mountain environments and contributes to a better understanding of landscape organization within the Pre-Atlasic domain of northeastern Algeria.

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Introduction:

Mountain landscapes are shaped by complex interactions among tectonic activity, lithological variability, climatic conditions, and surface processes such as erosion and sediment transport. In structurally controlled regions, terrain morphology and the organization of drainage networks often reflect the influence of tectonic deformation and long-term landscape evolution. Consequently, geomorphometric and morphotectonic analyses have become essential approaches for evaluating the relationships between tectonic processes and geomorphological development in mountainous environments.

Recent advances in satellite remote sensing and digital elevation models (DEMs) have greatly enhanced the ability to investigate geomorphological processes at regional scales. Moderate-resolution DEMs derived from the Shuttle Radar Topography Mission (SRTM) provide detailed topographic information that enables the extraction of terrain morphometric parameters and the quantitative analysis of drainage networks (Farr et al., 2007). Parameters such as slope, topographic position index (TPI), elevation-derived indices, and drainage density provide valuable indicators of landscape structure and erosional dynamics and can reveal spatial patterns related to tectonic uplift and differential erosion (Evans, 2012). When combined with Geographic Information System (GIS) techniques, these metrics allow the identification of ridge–valley structures, fluvial incision patterns, and geomorphological contrasts that characterize structurally controlled mountain belts.

The integration of geomorphometric analysis with multispectral satellite imagery further expands the potential for investigating landscape evolution. High-resolution satellite missions such as Sentinel-2 provide detailed spectral information that can be used to derive vegetation indices and monitor environmental variability (Drusch et al., 2012). Among these, the Normalized Difference Vegetation Index (NDVI) is widely used to quantify vegetation density and productivity and to assess ecosystem responses to environmental change (Tucker, 1979; Pettorelli et al., 2005). Because vegetation patterns are strongly influenced by topography, hydrology, and climatic conditions, analyzing vegetation indices together with terrain morphometry and drainage organization offers a comprehensive perspective on the interactions between surface processes and environmental gradients.

Recent developments in cloud-based geospatial platforms have further improved the capacity to process and analyze large volumes of remotely sensed data. Google Earth Engine (GEE) provides access to extensive geospatial datasets and computational resources that enable efficient implementation of regional-scale geomorphological and environmental analyses (Gorelick et al., 2017). The integration of DEM-derived terrain metrics with satellite-based vegetation indicators within a unified analytical environment facilitates the investigation of relationships among topography, hydrology, and ecosystem dynamics.

The Belezma–Batna anticline, located in northeastern Algeria near the city of Batna, provides an ideal setting for applying this integrated approach. This structure forms part of the Pre-Atlasic domain, which is characterized by compressional tectonics, folded Mesozoic sedimentary formations, and pronounced topographic relief. Tectonic processes associated with Alpine deformation have generated a series of anticlines and synclines that strongly influence the morphology of the region and the organization of its hydrographic networks (Khanchoul & Saaidia, 2017). As a result, the mountainous landscape exhibits marked geomorphological contrasts in which structural control, erosional processes, and environmental gradients interact to shape terrain morphology.

Despite the geomorphological importance of the Belezma massif, integrated investigations combining terrain morphometry, drainage organization, and satellite-derived vegetation dynamics remain limited. Previous studies conducted in northeastern Algeria have generally focused on watershed morphometry, erosion susceptibility assessment, morphotectonic analysis, or vegetation monitoring as separate topics (Khanchoul & Saaidia, 2017; Hadji et al., 2025; Barbachea et al., 2019). Consequently, a comprehensive assessment linking topographic structure, hydrological organization, and vegetation distribution within the Belezma–Batna anticline is still lacking.

To better understand the geomorphological evolution of this structurally controlled region, a multifaceted analytical framework is required. The objective of this study is therefore to analyze the terrain morphometry, drainage organization, and vegetation dynamics of the Belezma massif using integrated remote sensing and geomorphometric techniques. By combining DEM-derived terrain metrics with satellite-derived vegetation indices, this research evaluates the relationships between topography, hydrological organization, and vegetation distribution across the anticline structure. The resulting integrated framework provides new insights into the geomorphological evolution of the Belezma massif and contributes to a broader understanding of landscape development within the Pre-Atlasic domain of northeastern Algeria.

Geological setting:

The study area is located within the Belezma–Batna anticline, a prominent ENE–WSW-trending structure belonging to the Pre-Atlasic domain of northeastern Algeria. This structural domain forms a transitional belt between the Saharan Atlas and the Tellian Atlas and is characterized by compressional tectonics associated with the Alpine orogeny. These tectonic processes have deformed thick Mesozoic sedimentary successions into a series of faulted anticlines and synclines, producing the structurally controlled mountain landscapes typical of the region. The Belezma–Batna structure displays pronounced stratigraphic repetition, strong lithological contrasts, and a well-developed ridge–valley morphology, making it representative of the structural and geomorphological organization of the Pre-Atlasic domain.

The Belezma–Batna anticline is an elongated fold generated during the Alpine compressional phase that affected northeastern Algeria. The structure is characterized by asymmetrical flanks, local faulting, and significant tectonic shortening that contributed to the development of prominent ridge systems and marked topographic relief. Structural uplift associated with folding has strongly influenced drainage organization and landscape evolution throughout the massif. Consequently, the anticline constitutes the primary geomorphological framework controlling the distribution of topographic highs, valleys, and drainage networks within the study area.

The exposed stratigraphic succession ranges from the Triassic to the Quaternary (Figure 1; Bellion, 1972; Guiraud, 1973; Bureau, 1986; Yahiaoui, 1990; Herkat, 1999), reflecting the regional geological evolution from rift-related evaporitic environments to shallow marine carbonate platforms and later mixed siliciclastic–carbonate systems.

Triassic deposits consist predominantly of gypsiferous clays, marls, and evaporitic sequences, locally interbedded with dolomitic and volcano-sedimentary layers. These deposits formed during the early rifting phases of the Neo-Tethys and are generally mechanically weak and locally ductile. As a result, Triassic units are locally exposed within structural cores and tectonically disturbed sectors of the anticline. Their high clay and gypsum content promotes slope instability and facilitates drainage development.

The Jurassic succession is dominated by thick carbonate platform deposits. Lower–Middle Lias calcareous and dolomitic limestones form massive, thick-bedded, and highly competent units that constitute the structural backbone of the anticline. These resistant formations generate prominent ridges and steep slopes. Middle Jurassic intervals consist mainly of argillaceous limestones with chert nodules and siliceous horizons, reflecting deeper shelf depositional conditions and producing more fractured and dissected ridge morphology. The Oxfordian–Kimmeridgian interval, locally represented by Ammonitico Rosso facies, consists of marl–limestone alternations and nodular argillaceous limestones that introduce significant mechanical layering and transitional relief. During the Tithonian–Berriasian, micritic limestones mark a return to massive carbonate deposition, producing continuous ridge belts comparable in competence to the Lias carbonate units.

The Lower Cretaceous succession records an increase in terrigenous input and greater lithological heterogeneity. Upper Berriasian–Valanginian formations are composed mainly of marly–silty sandstones and fine siliciclastic deposits that are weakly consolidated and highly erodible, typically forming structural depressions and combes. In contrast, Hauterivian dolomitic–sandstone units, consisting of alternating dolomites and quartzitic sandstones, form mechanically resistant ridge belts. The Barremian–Lower Aptian succession comprises mixed clay-rich limestones, sandstones, and marls deposited in transitional shelf environments, producing intermediate mechanical behavior. Upper Aptian–Albian calcareous–marly formations display distinct vertical layering, with marl-dominated bases overlain by more resistant carbonate horizons, generating slope breaks and segmented ridge morphology.

The Upper Cretaceous succession further accentuates lithological contrasts. Lower Cenomanian marls form thick, weak slope-forming units, whereas Upper Cenomanian–Lower Turonian reefal and peri-reefal carbonates constitute highly competent ridge-forming bodies. Overlying Turonian marno-carbonate alternations produce transitional morphologies, followed by resistant Coniacian limestones that again form prominent ridges. Senonian marl-dominated deposits occupy valley floors and structural depressions and are commonly covered by Quaternary sediments.

Cenozoic deposits include Oligocene continental detrital formations and Miocene basin-fill sediments, composed mainly of sandstones and red beds that unconformably overlie older units. Quaternary deposits consist of glacis, alluvial sediments, and travertine accumulations that mantle valley bottoms and pediment surfaces.

The Belezma–Batna anticline exhibits a well-defined mechanical stratigraphy characterized by alternating competent carbonate units and weaker marl- and siliciclastic-dominated formations. This lithological architecture exerts a fundamental control on ridge–valley organization, slope development, drainage density, erosion patterns, and vegetation distribution. Resistant carbonate formations form elevated structural ridges, whereas weaker formations are preferentially eroded and occupy valleys and depressions. Consequently, the geological framework provides the primary control on the geomorphological and hydrological patterns analyzed in this study and offers an ideal natural laboratory for investigating interactions among tectonic structure, lithology, terrain morphology, drainage organization, and vegetation dynamics.

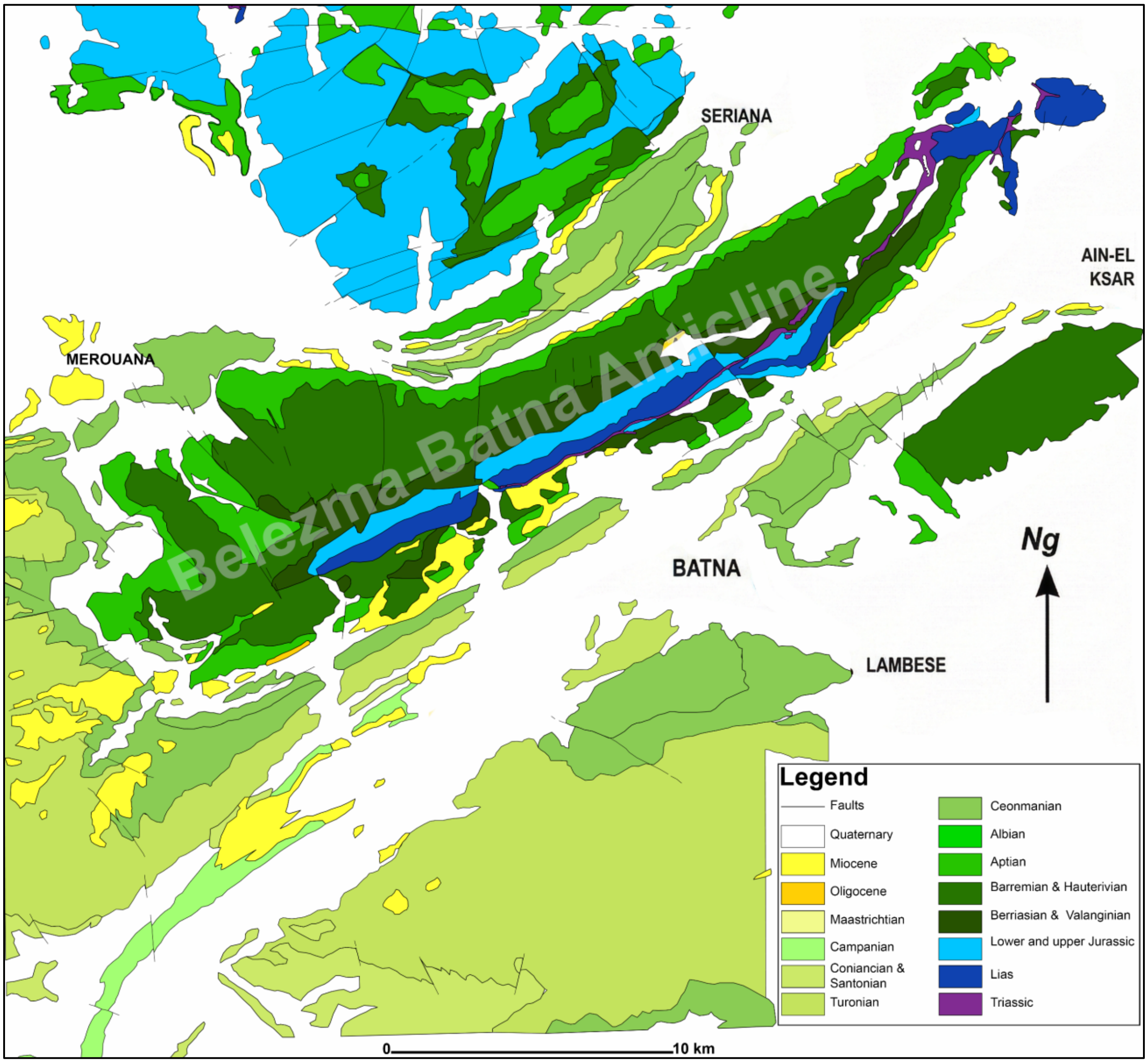

Figure.1. Geological map of the Belezma–Batna anticline in northeastern Algeria showing the main stratigraphic units and structural configuration of the study area (modified after Bureau, 1986)

Data and Methods

Data Sources

This study integrates digital elevation data and multispectral satellite imagery to analyze terrain morphometry, drainage organization, and vegetation dynamics in the Belezma massif in northeastern Algeria. Topographic analysis is based on a digital elevation model (DEM) derived from the Shuttle Radar Topography Mission (SRTM), which provides near-global elevation coverage at a spatial resolution of approximately 30 m. SRTM data have been widely used for morphometric and hydrological analyses due to their consistent spatial coverage and suitability for regional geomorphological investigations (Farr et al., 2007, Evans, 2012).

Vegetation dynamics and land surface characteristics were analyzed using multispectral satellite imagery from the Sentinel-2 constellation (Drusch et al., 2012). Sentinel-2 provides high-resolution optical imagery (10–20 m spatial resolution) with frequent revisit intervals, making it well suited for monitoring vegetation patterns and environmental variability. Surface reflectance products from the Sentinel-2 Level-2A archive were used. Images were filtered to retain scenes with less than 20% cloud cover and were composited for the period 2020–2025.

All datasets were processed using the cloud-based geospatial analysis platform Google Earth Engine, which enables efficient processing of large remote-sensing datasets and large-scale spatial analyses (Gorelick et al., 2017). Final cartographic products were prepared using QGIS.

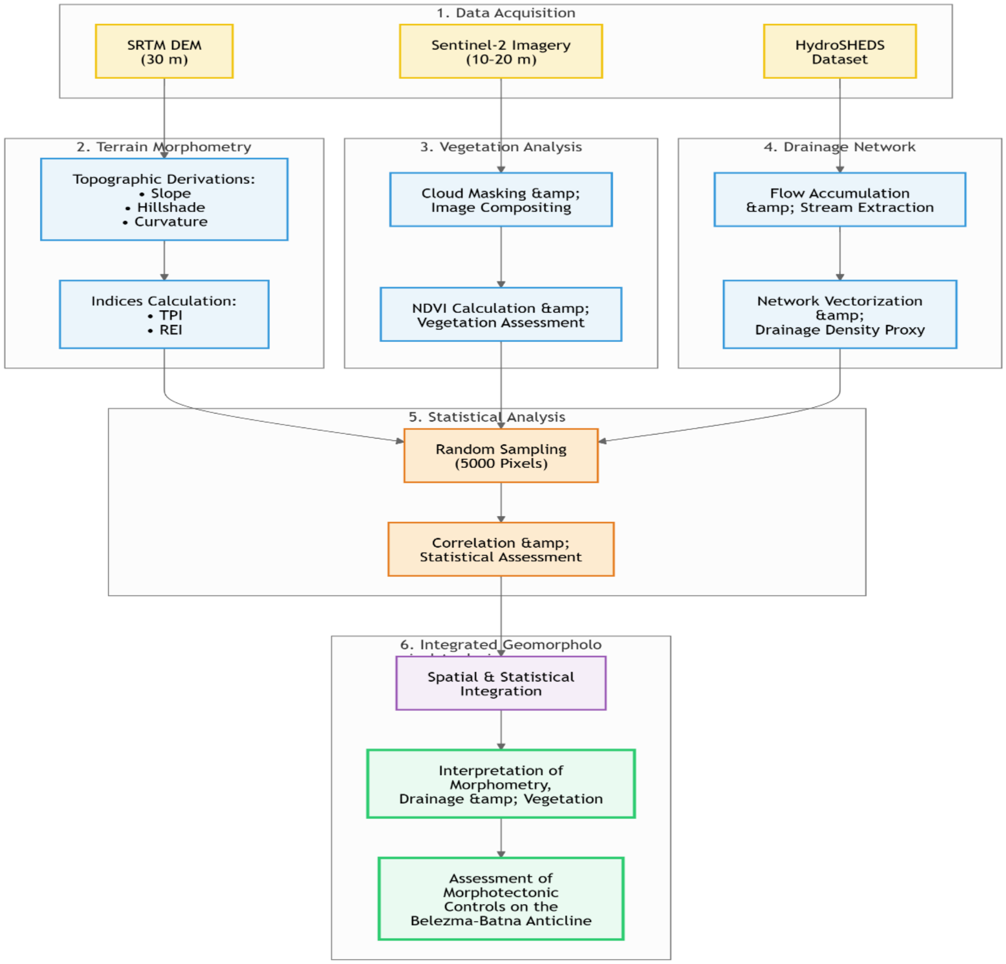

Fig. 2. Methodological workflow illustrating the integrated analysis used in this study, including DEM processing, terrain morphometric analysis, drainage extraction, NDVI calculation, and integrated geomorphological interpretation.

Digital Elevation Model Processing

The SRTM DEM was used as the primary dataset for terrain morphometric analysis. Several topographic derivatives were computed from the DEM using built-in terrain analysis functions available in Google Earth Engine.

The derived parameters include:

- **Slope gradient**, representing the steepness of the terrain and controlling erosion processes.
- **Hillshade**, generated from simulated illumination conditions to enhance the visualization of terrain morphology and structural lineaments.

In addition, the **Topographic Position Index (TPI)** was calculated to characterize local relief variations and identify ridge and valley structures. TPI was computed by subtracting the mean elevation within a 500 m moving window from the elevation of each pixel. Positive TPI values correspond to ridges and elevated terrain, whereas negative values represent valley bottoms and concave landforms.

Terrain curvature was also derived from the DEM using a Laplacian convolution operator implemented in Google Earth Engine. Curvature provides information on the convexity and concavity of landforms and assists in identifying ridge crests, valley bottoms, and transitional slope elements. Positive values correspond to convex surfaces, whereas negative values indicate concave terrain.

These morphometric parameters provide quantitative descriptors of terrain morphology and are widely used to analyze landscape structure, erosion patterns, and structural controls on topography (Evans, 2012).

Drainage Network Extraction and Hydrological Metrics

Drainage organization was analyzed using the global flow accumulation dataset from the HydroSHEDS database, which is derived from hydrologically conditioned SRTM elevation data (Lehner et al., 2011). Flow accumulation represents the upstream contributing area for each pixel and is widely used to delineate river networks and watershed structures.

Stream channels were extracted using a flow accumulation threshold value of 20 cells. This threshold was selected after visual calibration to produce a drainage network that best matched the observed hydrographic organization of the Belezma massif while minimizing noise from minor ephemeral channels. The resulting drainage network was converted into vector features to facilitate visualization and further spatial analysis.

To evaluate hydrological organization across the Belezma massif, a drainage density proxy was derived using a moving-window approach that calculates the concentration of stream pixels within a circular neighborhood of 2 km radius. Higher values indicate greater fluvial dissection and channel concentration. The spatial distribution of this metric reflects the combined influence of lithology, structural controls, slope gradients, and hydrological processes.

Additionally, a Relative Elevation Index (REI) was calculated to characterize the spatial distribution of relative elevation across the Belezma massif. The index was obtained by normalizing elevation values according to:

$$REI = \frac{E - E_{min}}{E_{max} - E_{min}}$$

where E represents elevation, Emin is the minimum elevation within the study area, and Emax is the maximum elevation. Values approaching 1 correspond to elevated ridge crests and mountain summits, whereas values approaching 0 indicate valley bottoms and low-relief sectors. The REI provides a useful representation of relative topographic position and geomorphological organization within the anticline.

Vegetation Analysis

Vegetation distribution and density were analyzed using multispectral imagery from the Sentinel-2 satellite mission. A median composite of cloud-free images acquired between 2020 and 2025 was generated after applying cloud-masking procedures based on the QA60 quality band. Only scenes with less than 20% cloud cover were retained for analysis.

Vegetation patterns were quantified using the Normalized Difference Vegetation Index (NDVI), a widely used spectral index that measures vegetation vigor, biomass, and photosynthetic activity from satellite imagery (Tucker, 1979; Pettorelli et al., 2005). The NDVI was calculated according to:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

where **NIR** corresponds to near-infrared reflectance (Band 8 in Sentinel-2) and **Red** corresponds to red reflectance (Band 4).

NDVI values range from −1 to +1, with higher positive values indicating dense and healthy vegetation cover. Spatial variations in NDVI provide insights into vegetation density, land-cover patterns, and eco-hydrological gradients across the mountainous landscape.

Integrated Geomorphological Analysis

The derived terrain morphometric parameters (slope, hillshade, TPI, curvature, and Relative Elevation Index), hydrological variables (drainage network and drainage density proxy), and vegetation metrics (NDVI) were integrated to investigate the geomorphological structure of the Belezma massif, following established terrain-analysis approaches (Wilson & Gallant, 2000).

Spatial relationships between terrain morphology, drainage organization, and vegetation distribution were evaluated through spatial overlay analysis within the GIS environment. Particular attention was given to the relationship between ridge–valley morphology, fluvial incision patterns, and vegetation gradients.

To further investigate interactions among environmental variables, random sampling points were generated across the study area. Elevation and NDVI values, as well as slope and drainage density values, were extracted from 5000 sampled pixels. These datasets were subsequently used for exploratory statistical analysis and correlation assessment in order to evaluate relationships between topography, hydrological organization, and vegetation distribution.

By comparing the spatial distribution of morphometric indices with the structural configuration of the Belezma–Batna anticline, areas influenced by tectonic uplift were distinguished from zones dominated by erosional processes and differential weathering.

The integration of DEM-derived morphometric analysis with multispectral vegetation data provides a comprehensive framework for understanding the interactions between tectonic forcing, topographic structure, hydrological organization, and ecological dynamics in this structurally controlled mountain environment.

Results

Topographic characteristics of the Belezma-Batna Anticline

The Digital Elevation Model (DEM) (Figure 3) highlights the complex topographic structure of the Belezma–Batna anticline, characterized by pronounced relief and a strong altitudinal gradient between the surrounding plains and the central mountainous ridge. Elevation within the study area reaches approximately 2157 m above sea level, with a mean elevation of approximately 1149 m and a standard deviation of 283.5 m, indicating substantial topographic variability across the massif.

Elevations progressively increase from the peripheral areas toward the core of the massif, where the highest peaks form an elongated ridge system extending predominantly in an ENE–WSW direction. This ridge constitutes the principal morphological axis of the massif and represents the main topographic divide controlling regional drainage patterns.

Several secondary ridges branch from this central structure, creating a highly dissected terrain characterized by numerous valleys and tributary systems. The northern and southern margins of the massif gradually transition toward lower-relief areas dominated by piedmont surfaces and alluvial plains.

The DEM further reveals that the highest elevations are concentrated within the central mountainous sector between Merouana and Batna, where topographic gradients are particularly pronounced. In contrast, the western and eastern margins exhibit smoother terrain morphology and lower relief amplitudes. The marked elevation contrast between ridge crests and adjacent valleys reflects the combined influence of tectonic uplift, differential erosion, and lithological contrasts among the sedimentary formations that compose the anticline.

The spatial organization of elevation across the study area demonstrates the strong structural control exerted by the Belezma–Batna anticline. The alignment of the principal ridge system closely follows the regional tectonic trend, indicating that present-day topography remains strongly conditioned by geological structure despite prolonged erosional modification.

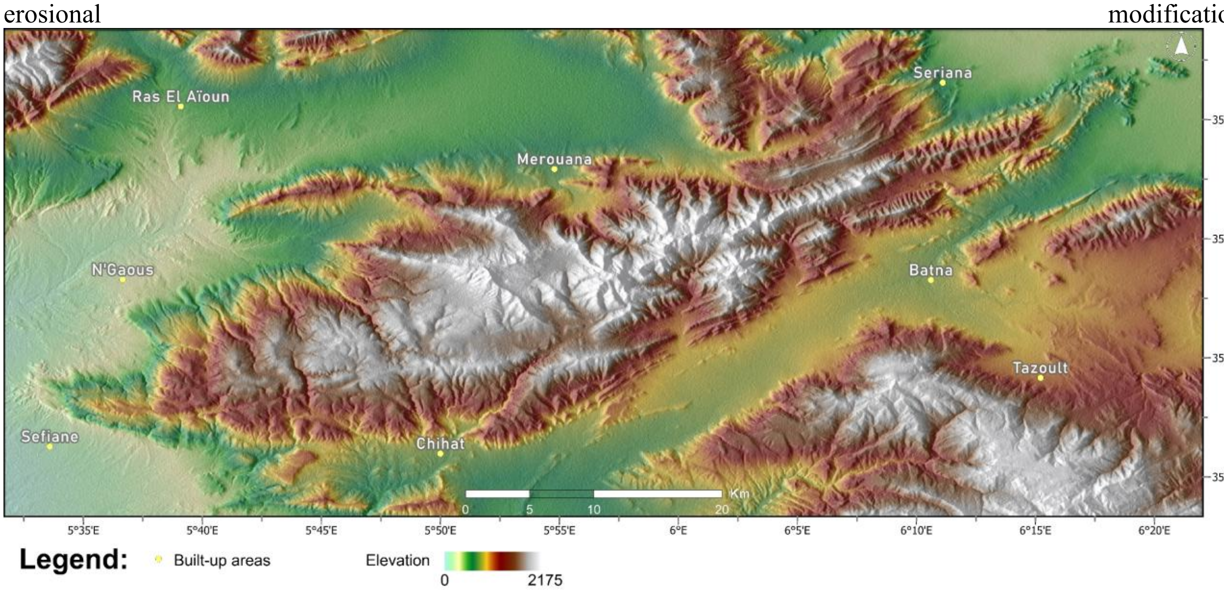

Fig.3: Digital Elevation Model (DEM) of the Belezma–Batna anticline derived from SRTM data. The map highlights the pronounced ridge–valley morphology, strong altitudinal gradients, and ENE–WSW structural organization of the massif.

Slope distribution and relief intensity

Slope analysis provides important insights into the relief intensity and geomorphological dynamics of the Belezma–Batna anticline. The slope map (Figure 4) reveals strong spatial variability in terrain steepness, reflecting the highly dissected nature of the massif. Slope values range from 0° to 43.84°, with a mean slope of 6.84° (Table 1), indicating that low-to-moderate gradients dominate much of the study area while steep slopes remain concentrated within the mountainous core of the anticline.

Low slope values (generally below 5°) dominate valley bottoms and the surrounding plains, where fluvial deposition and sediment accumulation have produced relatively flat surfaces. These low-gradient areas are mainly associated with alluvial plains, piedmont zones, and structural depressions surrounding the mountain range.

Moderate slopes (between 5° and 15°) are primarily observed along transitional zones connecting mountain ridges with adjacent lowlands. These intermediate-gradient sectors represent areas where erosional and depositional processes coexist and where hillslope evolution is strongly influenced by surface runoff and weathering processes.

Steep slopes exceeding 15° are concentrated along the central ridges and mountainous sectors of the massif. These areas correspond to zones of high relief energy where gravitational processes, surface runoff, and active erosion contribute significantly to landscape development. The steepest slopes are commonly associated with structurally controlled ridges, escarpments, and resistant carbonate formations that form the topographic backbone of the anticline.

The spatial distribution of steep slopes closely follows the ENE–WSW structural trend of the Belezma–Batna anticline, indicating strong tectonic and lithological control on topographic development. Resistant Jurassic and Upper Cretaceous carbonate formations generally correspond to high-gradient ridge sectors, whereas marl-rich and siliciclastic units are associated with gentler slopes and broader valley floors. This relationship highlights the influence of differential erosion acting upon formations of contrasting mechanical resistance.

Overall, the slope distribution highlights the pronounced geomorphological contrast between the mountainous core of the anticline and the surrounding piedmont zones. The observed pattern reflects the combined effects of tectonic uplift, lithological control, and long-term erosional processes that have shaped the present-day landscape of the Belezma massif.nal processes that have shaped the present-day landscape of the Belezma massif.

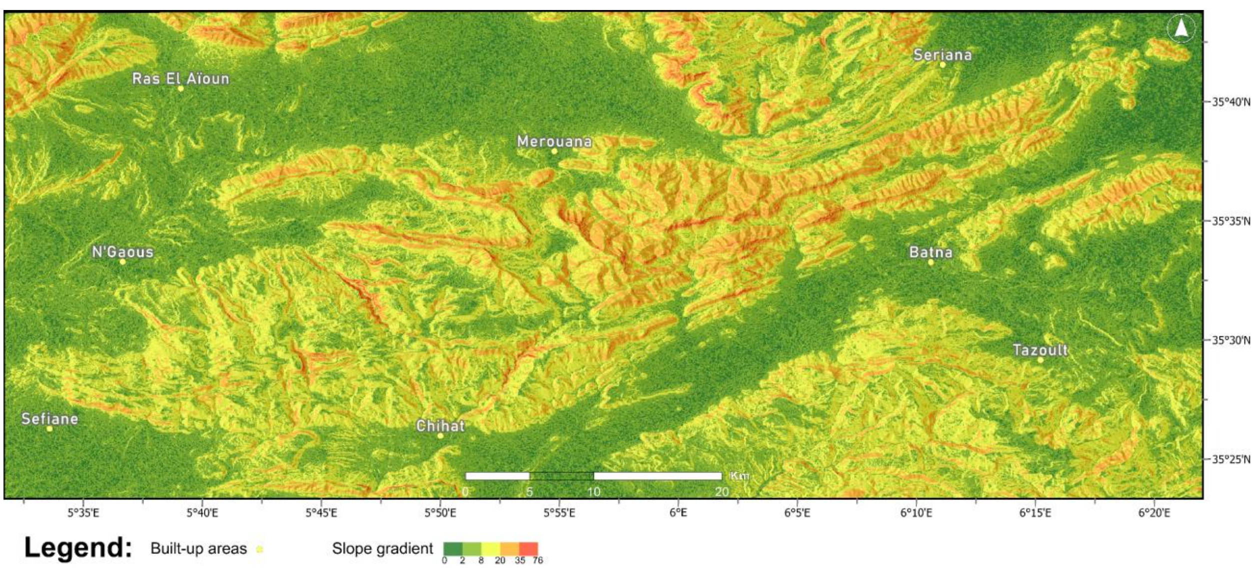

Fig.4: Slope gradient map derived from the SRTM 30 m DEM showing the spatial distribution of terrain steepness across the Belezma–Batna anticline. Steep slopes are concentrated along structurally controlled ridges and escarpments, whereas low-gradient areas dominate valley bottoms and piedmont surfaces.

Table 1. Summary statistics of terrain morphometric parameters derived from the DEM

Parameter	**Minimum**	**Maximum**	**Mean**
Slope (°)	0	43.84	6.84
Drainage density	5.4×10^{-5}	3.65×10^{-4}	1.84×10^{-4}
Curvature	−7767	345	-3.44

Topographic Position Index (TPI)

The Topographic Position Index (TPI) provides information on the relative position of terrain features within the landscape by comparing the elevation of each pixel with the mean elevation of its surrounding neighborhood. This metric is particularly useful for distinguishing ridge crests, valley bottoms, and intermediate slope positions and for characterizing landscape organization within structurally controlled mountain environments.

The TPI map (Figure 5) highlights the pronounced geomorphological contrast across the Belezma–Batna anticline. Positive TPI values correspond to elevated terrain features such as ridge crests, hilltops, and structurally controlled mountain ridges. These positive anomalies are concentrated along the central ENE–WSW-trending ridge system, which constitutes the principal structural framework of the massif and controls both drainage organization and topographic development.

Negative TPI values identify valley bottoms, drainage corridors, and incised erosional features where runoff concentration and sediment transport are most active. These areas are primarily distributed between the major ridge systems and coincide with the principal fluvial channels and their tributary networks. The concentration of negative TPI values within narrow linear depressions reflects the advanced dissection of the mountain landscape by erosional processes.

Intermediate TPI values represent hillslopes and transitional terrain connecting ridge crests to valley floors. These slope elements constitute the dominant geomorphological component across much of the study area and reflect the progressive transition between erosional and depositional environments.

Overall, the spatial distribution of TPI values confirms the strongly dissected morphology of the Belezma massif and emphasizes the structural control exerted by the Belezma–Batna anticline on landscape organization. The alignment of positive TPI anomalies along the principal tectonic trend demonstrates the close relationship between geological structure and present-day topography.

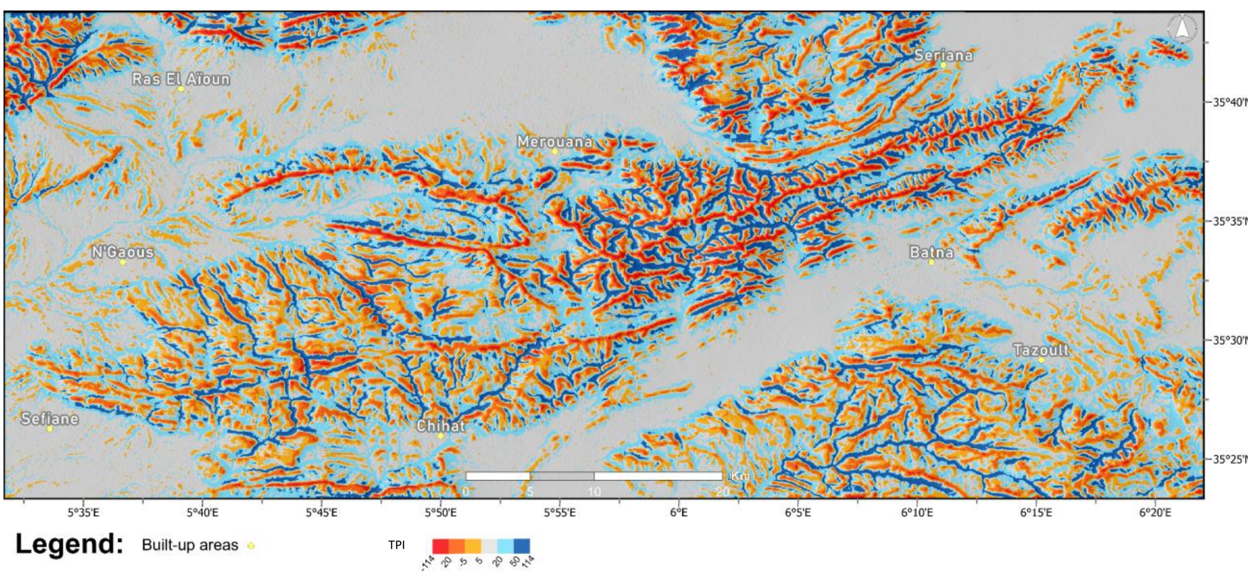

Fig.5: Topographic Position Index (TPI) calculated from the SRTM DEM highlighting ridge crests (positive values), valley bottoms (negative values), and intermediate slope positions within the Belezma massif.

Terrain curvature analysis further highlights the variability of landform morphology across the massif. Curvature values range from strongly concave surfaces (−7767) to convex ridge crests reaching values of approximately 345. The large range of curvature values indicates a highly dissected landscape characterized by alternating ridge crests, steep slopes, and deeply incised valleys. The relatively high curvature variability is consistent with the structurally controlled ridge–valley morphology observed in the DEM and TPI analyses.

Terrain Curvature

Terrain curvature analysis further highlights the variability of landform morphology across the massif. Curvature values range from −7767 to 345, with a mean value of −3.44 (Table 1). Negative curvature values correspond to concave landforms such as valleys, drainage channels, and erosional depressions, whereas positive values characterize convex features including ridge crests and topographic highs.

The predominance of slightly negative curvature values indicates that concave terrain elements occupy a substantial proportion of the landscape. Areas exhibiting strong negative curvature are generally associated with deeply incised valleys and concentrated drainage pathways, while positive curvature values are concentrated along structurally controlled ridges and escarpments.

The large range of curvature values reflects the highly dissected nature of the Belezma massif and is consistent with the ridge–valley morphology identified from the DEM and TPI analyses. Together, these results indicate that tectonic structure and differential erosion have played a fundamental role in shaping the present-day geomorphological configuration of the massif.

Drainage network organization

The drainage network extracted from the DEM (Figure 6) reveals a well-developed fluvial system that reflects both topographic gradients and structural controls within the Belezma–Batna anticline. The drainage pattern is predominantly dendritic to sub-dendritic, although local channel orientations indicate the influence of geological structures and ridge alignment on drainage development.

Most streams originate along the central mountainous ridge and flow toward the surrounding lowlands. This bidirectional drainage organization reflects the role of the principal ridge as a major topographic divide separating northward- and southward-flowing catchments. Numerous tributaries converge into larger channels, producing a hierarchical drainage system characteristic of mountainous landscapes undergoing active fluvial dissection.

Several sectors display drainage alignments that parallel ridge orientations and structural lineaments, suggesting that tectonic structure exerts a significant influence on channel development. This structural control is particularly evident along elongated valleys and linear drainage segments associated with the ENE–WSW orientation of the anticline.

The dense concentration of tributaries observed on steep mountain slopes indicates active surface runoff and ongoing erosional processes. In contrast, lower-relief piedmont areas exhibit a more diffuse drainage organization characterized by wider channel spacing and reduced drainage density.

Overall, the drainage network reflects the combined influence of topography, geological structure, and fluvial erosion in shaping the present-day landscape of the Belezma massif. The close correspondence between drainage organization and ridge–valley morphology further supports the strong structural control exerted by the Belezma–Batna anticline on geomorphological development.

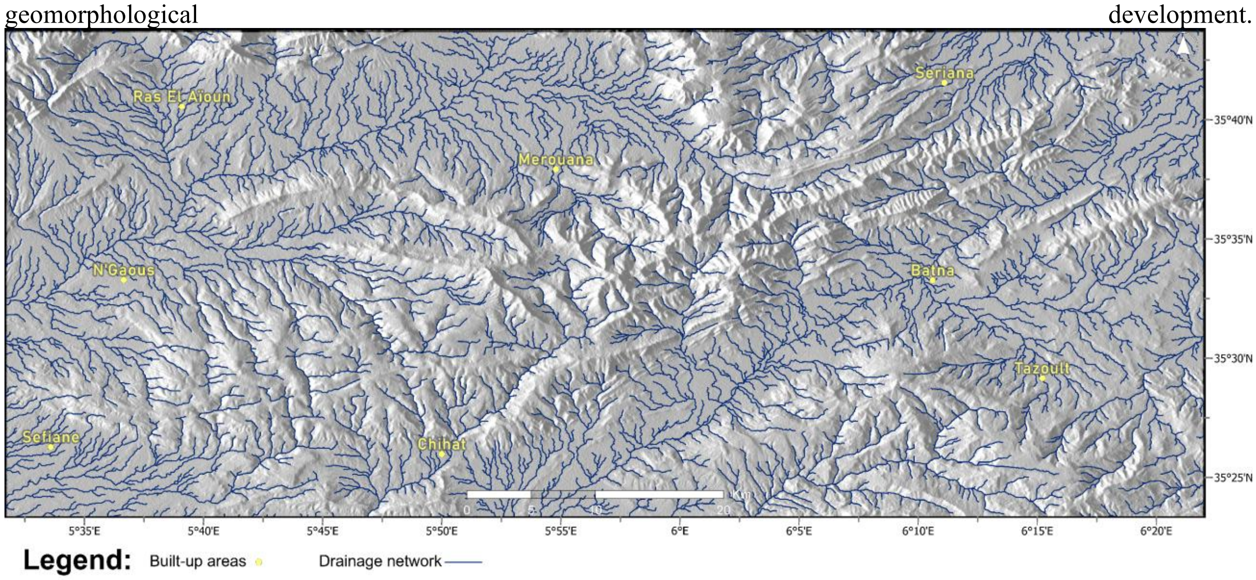

Fig.6 Drainage network extracted from HydroSHEDS flow accumulation data and superimposed on a hillshade model derived from the SRTM DEM. The map illustrates the hierarchical organization of fluvial channels and the influence of ridge–valley morphology on drainage development within the Belezma–Batna anticline.

Spatial distribution of drainage density

Drainage density analysis provides valuable information regarding the intensity of fluvial dissection and hydrological organization across the Belezma–Batna anticline. The drainage density map (Figure 7) reveals marked spatial variability, reflecting the combined influence of topography, geological structure, and erosional processes.

Higher drainage density values are concentrated within dissected valley systems and sectors characterized by well-developed tributary networks. These areas indicate active fluvial incision and efficient drainage organization, where runoff is concentrated into numerous channels. In contrast, lower drainage density values are generally associated with ridge crests, elevated structural highs, and peripheral low-relief sectors where channel development is less pronounced.

Intermediate drainage density values occur along mountain flanks and transitional piedmont zones, representing areas where channel development remains significant but less intense than in the most dissected valley systems. The observed spatial pattern reflects the influence of lithological contrasts, structural controls, slope gradients, and hydrological processes on channel development.

Overall, the drainage density distribution highlights the heterogeneous nature of fluvial dissection across the massif and confirms the strong influence of ridge–valley organization on drainage development.

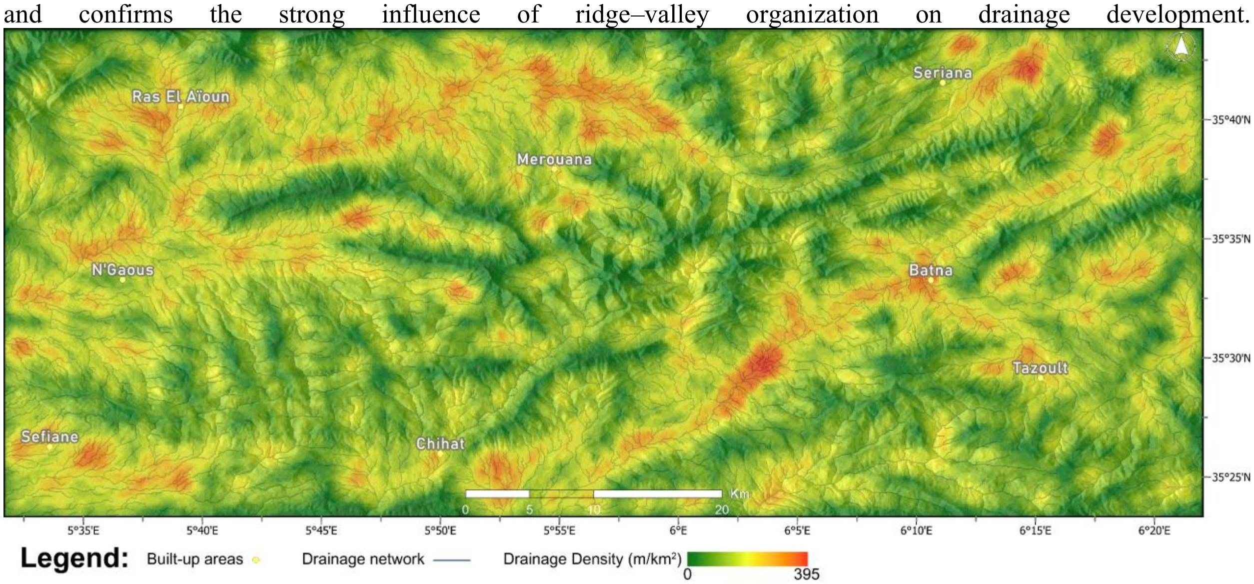

Fig.7 : Drainage density distribution across the Belezma–Batna anticline indicating areas of intense fluvial dissection and sectors characterized by lower drainage development.

To further investigate the relationship between terrain morphology and hydrological organization, drainage density values were compared with slope gradients using 611 sampled terrain points extracted from the study area. The resulting scatter plot (Figure 8) reveals a weak negative correlation between slope and drainage density (Pearson $r = -0.208$; $R^2 = 0.043$). Although the relationship is statistically weak, the negative trend indicates that drainage density tends to decrease slightly with increasing slope.

This pattern reflects the geomorphological organization of the Belezma massif, where dense drainage networks are preferentially developed within moderately sloping valley systems and dissected terrain, whereas the steepest slopes are commonly associated with ridge crests and escarpments that support fewer channel segments. The low coefficient of determination further suggests that drainage density is controlled by multiple factors beyond slope alone, including lithology, structural configuration, soil characteristics, and local hydrological conditions.

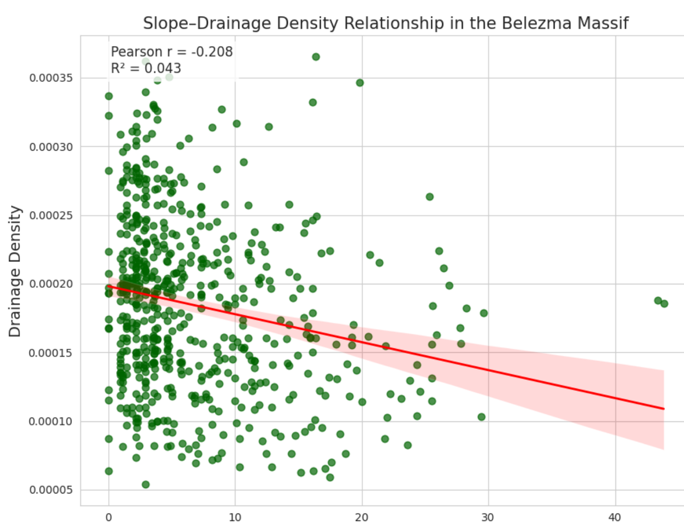

Fig.8 : Relationship between slope gradient and drainage density in the Belezma massif derived from 611 sampled terrain points. The weak negative correlation ($r = -0.208$; $R^2 = 0.043$) indicates that drainage networks tend to concentrate within moderately sloping valley sectors rather than on steep ridge crests.

Morphometric Correlation Analysis

The morphometric correlation matrix (Figure 9) confirms the weak negative relationship between slope and drainage density (r = −0.21). The low magnitude of the correlation coefficient indicates that slope alone exerts limited control on drainage density across the massif. Instead, the observed drainage organization likely reflects the combined influence of topography, lithological variability, structural controls, and erosional processes operating within the anticline.

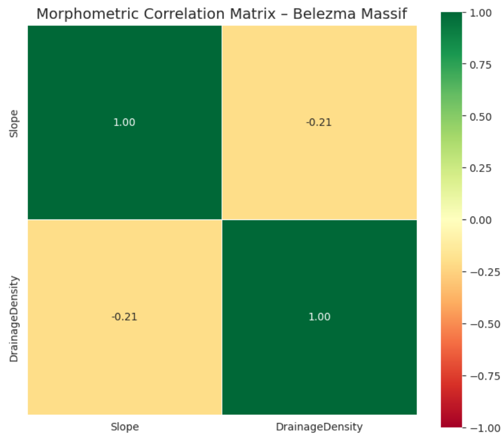

Figure 9. Correlation matrix showing the relationship between slope gradient and drainage density within the Belezma massif.

Relative Elevation Index (REI) and Topographic Organization

The Relative Elevation Index (REI) provides a normalized representation of elevation across the Belezma–Batna anticline and highlights the relative position of topographic features within the landscape. The index ranges from values approaching 0 in low-lying sectors to values approaching 1 in the highest parts of the massif.

The REI map (Figure 10) reveals a clear spatial differentiation between elevated ridge systems and surrounding lower-relief areas. High REI values are concentrated along the principal mountain ridges and summit zones, particularly within the central ENE–WSW-trending structural axis of the anticline. These areas correspond to the highest elevations of the massif and define the principal topographic framework of the region.

Intermediate REI values characterize hillslopes and transitional terrain located between ridge crests and valley bottoms. These zones occupy a substantial proportion of the study area and represent the gradual transition between elevated structural highs and lower-relief sectors.

Low REI values are primarily associated with valley bottoms, drainage corridors, piedmont zones, and peripheral plains. These areas correspond to the lowest topographic positions within the landscape and frequently coincide with major fluvial pathways and sediment accumulation zones.

The spatial distribution of REI values closely follows the structural configuration of the Belezma–Batna anticline, emphasizing the strong relationship between geological structure and topographic organization. High REI zones correspond to structurally elevated ridge systems, whereas low REI values delineate valleys and depressions shaped by erosional processes.

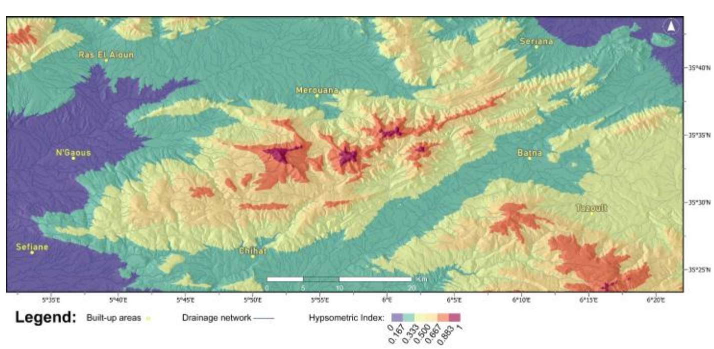

Figure.10 : Relative Elevation Index (REI) derived from the SRTM DEM showing the spatial distribution of normalized elevation across the Belezma–Batna anticline. High values correspond to elevated ridge systems and summit zones, whereas low values identify valleys, drainage corridors, and peripheral low-relief sectors.

REI

Vegetation distribution derived from NDVI

The Normalized Difference Vegetation Index (NDVI) map (Figure 11) provides a detailed representation of vegetation distribution across the Belezma–Batna anticline. NDVI values range from approximately −0.38 to 0.83, indicating substantial spatial variability in vegetation cover and biomass throughout the study area.

Higher NDVI values (> 0.45) are concentrated within the mountainous sectors of the massif, particularly along forested slopes and elevated ridge systems. These areas correspond to dense vegetation cover and are associated with favorable moisture conditions, relatively lower anthropogenic disturbance, and well-developed forest ecosystems. The highest NDVI values are observed within the central mountainous zone, where topographic and climatic conditions support sustained vegetation growth.

Intermediate NDVI values (approximately 0.20–0.45) characterize transitional zones dominated by shrublands, open woodlands, and mixed vegetation communities. These areas are primarily distributed along mountain flanks and foothill regions and reflect moderate vegetation density under variable environmental conditions.

Lower NDVI values (< 0.20) occur predominantly within cultivated lands, sparsely vegetated surfaces, urbanized areas, and exposed rocky terrain. These zones are particularly evident within the surrounding plains and lower-elevation sectors, where vegetation cover is generally less dense and more strongly influenced by seasonal climatic variability and human land use.

The spatial distribution of NDVI demonstrates a strong relationship between vegetation cover and topographic organization. Elevated mountainous sectors generally support denser vegetation than adjacent lowlands, reflecting the combined influence of altitude, moisture availability, soil development, and geomorphological conditions. This pattern highlights the important role of topography in controlling vegetation distribution across the Belezma massif.

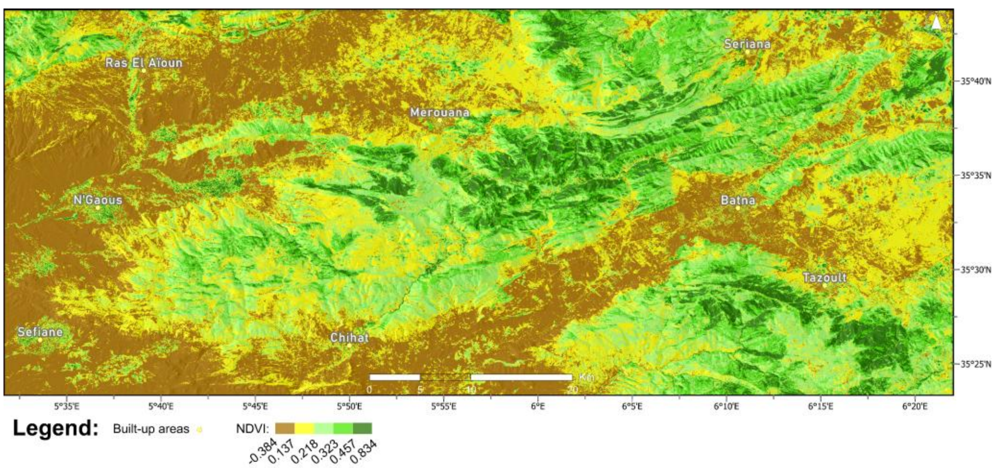

Figure 11. Normalized Difference Vegetation Index (NDVI) derived from Sentinel-2 imagery showing the spatial distribution of vegetation density across the Belezma–Batna anticline. Higher values indicate dense vegetation cover and forested sectors, whereas lower values correspond to sparsely vegetated surfaces, cultivated lands, and exposed terrain.

Discussion

Structural control on terrain morphology

The morphometric analysis clearly demonstrates that the present-day topography of the Belezma–Batna anticline is strongly controlled by its geological structure. The elongated ridge system identified in the DEM corresponds closely to the ENE–WSW orientation of the anticline axis described in the geological framework. This structural alignment governs the spatial organization of elevation, slope gradients, drainage organization, and ridge–valley morphology across the study area.

Resistant carbonate formations, particularly the Lower–Middle Jurassic limestones and the Upper Cenomanian–Turonian carbonate units, form the most prominent topographic highs within the massif. These competent lithologies generate continuous ridges with steep slopes and relatively limited erosion, producing the high-elevation belt observed along the central part of the anticline. In contrast, weaker marl-dominated formations such as the Cenomanian and Senonian deposits tend to occupy structural depressions and valley bottoms where erosion is more effective.

The distribution of slope gradients, TPI values, and Relative Elevation Index (REI) values further supports this structural control. Positive TPI values, high REI values, and steep slopes coincide with ridge crests developed on resistant carbonate formations, whereas negative TPI values and low REI values correspond to valley floors preferentially eroded within weaker lithologies. This pattern reflects the mechanical stratigraphy of the anticline, where alternating resistant and weak units produce the characteristic ridge–valley morphology commonly observed in fold-and-thrust mountain belts.

Similar relationships between geological structure, lithological resistance, and terrain morphology have been reported in other structurally controlled mountain regions. Studies conducted in northeastern Algeria have demonstrated that tectonic deformation and lithological contrasts exert a primary influence on drainage organization and geomorphological development (Khanchoul & Saaidia, 2017). Comparable morphotectonic controls have also been documented in folded mountain belts of the Betic Cordillera and the Zagros Fold–Thrust Belt, where resistant carbonate units form prominent structural ridges while weaker formations preferentially undergo erosion (Pedrera et al., 2009; Zebari & Burberry, 2015).

The close correspondence observed between geological structure and geomorphological organization within the Belezma massif therefore indicates that tectonic inheritance remains a dominant control on landscape evolution. Although erosional processes continue to modify the terrain, the present-day topography largely preserves the structural framework imposed by Alpine deformation and subsequent differential erosion.

Drainage organization and fluvial incision

The drainage network extracted from the DEM exhibits a predominantly dendritic to sub-dendritic pattern, indicating that topography exerts a stronger influence on drainage organization than localized lithological contrasts at the regional scale. Nevertheless, the spatial arrangement of channels reveals a clear relationship with both topographic gradients and structural orientation within the Belezma–Batna anticline.

Most channels originate along the central mountainous ridge and flow toward the surrounding lowlands. This bidirectional drainage organization reflects the role of the principal ridge as a major watershed divide separating northward- and southward-flowing catchments. The observed drainage configuration demonstrates the strong influence of the anticline on surface runoff distribution and hydrological organization across the massif.

Several sectors display drainage alignments that parallel ridge orientations and structural lineaments, suggesting that tectonic structures locally influence channel development and fluvial incision. This structural control is particularly evident along elongated valleys and linear drainage segments that follow the ENE–WSW orientation of the anticline. The presence of numerous tributaries on mountain slopes further indicates active erosional processes driven by strong relief gradients and concentrated surface runoff.

Drainage density analysis reveals substantial spatial variability across the study area. Areas characterized by high drainage density correspond primarily to dissected valley systems and sectors with well-developed tributary networks, reflecting active fluvial incision and efficient channel development. In contrast, lower drainage density values are generally associated with ridge crests, structurally elevated sectors, and low-relief peripheral areas where channel development is less pronounced.

The weak negative correlation observed between slope and drainage density ($r = -0.208$; $R^2 = 0.043$) indicates that drainage density is not controlled by slope alone. Instead, the observed pattern reflects the combined influence of lithological resistance, structural configuration, hydrological processes, and topographic organization. Dense drainage networks tend to occur within moderately sloping valley systems rather than on the steepest ridge sectors, highlighting the importance of geomorphological setting in controlling fluvial dissection.

These observations are consistent with previous morphometric studies conducted in northeastern Algeria, which emphasize the importance of tectonic structure and lithological contrasts in controlling drainage organization and landscape evolution (Khanchoul & Saaidia, 2017). Similar relationships between structural control, drainage development, and fluvial incision have also been reported in other folded mountain belts such as the Betic Cordillera and the Zagros Fold–Thrust Belt (Pedrera et al., 2009; Zebari & Burberry, 2015).

Overall, the drainage network of the Belezma massif reflects the combined effects of tectonic inheritance, lithological variability, and ongoing erosional processes. Although fluvial incision continues to modify the landscape, the organization of the drainage system remains strongly conditioned by the structural framework of the Belezma–Batna anticline.

Landscape evolution and geomorphological maturity

The Relative Elevation Index (REI) provides valuable insights into the spatial organization of topography within the Belezma–Batna anticline. By normalizing elevation values across the study area, the index highlights the relative position of ridge crests, slopes, and valley systems and facilitates the interpretation of large-scale topographic patterns.

High REI values are concentrated along the principal ridge systems and elevated sectors of the massif. These areas correspond to structurally controlled topographic highs that define the main geomorphological framework of the anticline. The concentration of high REI values along the ENE–WSW-trending ridge axis reflects the strong influence of geological structure on landscape organization.

Intermediate REI values characterize hillslopes and transitional terrain situated between ridge crests and valley bottoms. These sectors occupy a substantial proportion of the study area and represent the gradual transition from elevated structural highs to lower-relief environments. The distribution of intermediate values corresponds closely with the slope patterns identified in the morphometric analysis.

Low REI values are primarily associated with valley bottoms, drainage corridors, piedmont zones, and peripheral plains. These areas represent the lowest topographic positions within the landscape and frequently coincide with major drainage pathways identified in the hydrological analysis. The concentration of low REI values along fluvial corridors further emphasizes the important role of erosion and drainage organization in shaping local relief.

The spatial distribution of REI values demonstrates the strong correspondence between topography, geological structure, and drainage organization within the Belezma massif. High REI values delineate the structurally elevated ridge systems, whereas low REI values identify erosional depressions and valley networks. Together with the DEM, slope, TPI, and drainage analyses, the REI results confirm that the present-day landscape remains strongly conditioned by the structural framework of the Belezma–Batna anticline.

Similar relationships between relative elevation patterns and structural organization have been reported in other folded mountain belts, where tectonic uplift and differential erosion interact to produce characteristic ridge–valley morphologies (Pedrera et al., 2009; Zebari & Burberry, 2015). The Belezma massif exhibits a comparable geomorphological configuration, reflecting the long-term influence of tectonic structure on topographic development.

Vegetation patterns and topographic controls

The NDVI analysis reveals that vegetation distribution across the Belezma–Batna anticline is closely linked to topographic conditions, hydrological organization, and land-use patterns. High NDVI values are predominantly concentrated within the mountainous sectors of the massif, particularly on forested slopes and elevated ridge systems where environmental conditions favor the development of dense vegetation cover. These areas benefit from relatively higher moisture availability, reduced anthropogenic disturbance, and well-developed forest ecosystems.

In contrast, lower NDVI values are primarily associated with valley bottoms, cultivated lands, sparsely vegetated surfaces, and surrounding plains. In these sectors, vegetation density is influenced by seasonal climatic variability, agricultural activities, grazing pressure, and local soil conditions. The presence of exposed bedrock and thin vegetation cover in some lowland areas further contributes to reduced NDVI values.

Topography exerts a significant influence on vegetation distribution through its control on microclimatic conditions, soil development, and water availability. Elevation gradients influence temperature and moisture regimes, while terrain morphology affects runoff concentration, infiltration, and soil accumulation. Consequently, different geomorphological settings provide contrasting environmental conditions that support distinct vegetation communities.

The observed relationship between vegetation cover and topography is consistent with the geomorphological organization identified through the DEM, slope, TPI, and REI analyses. Forested sectors generally correspond to elevated and structurally controlled mountain areas, whereas lower NDVI values are more common in valley systems and peripheral plains. This spatial pattern demonstrates the close interaction between terrain morphology and ecological processes within the massif.

These findings are consistent with previous studies that have demonstrated the strong influence of topography on vegetation distribution in Mediterranean and semi-arid mountain environments (Pettorelli et al., 2005; Berbachea et al., 2019). In the Belezma massif, vegetation patterns appear to reflect the combined effects of altitude, hydrological conditions, geomorphological setting, and human land use. The spatial correspondence between NDVI distribution and topographic organization therefore highlights the important role of terrain controls in shaping ecosystem structure across the anticline.

Integrated geomorphological interpretation

The integration of terrain morphometry, drainage organization, and vegetation analysis provides a comprehensive understanding of the geomorphological structure of the Belezma–Batna anticline. The combined results consistently indicate that the present-day landscape is fundamentally controlled by the geological framework of the anticline, with topographic development closely reflecting lithological contrasts and structural configuration.

The morphometric analyses demonstrate that resistant carbonate formations form the principal ridge systems and elevated sectors of the massif, whereas weaker marl-rich and siliciclastic units preferentially occupy valleys and structural depressions. This lithological control is clearly expressed in the spatial distribution of elevation, slope gradients, TPI values, curvature patterns, and Relative Elevation Index (REI) values. Together, these parameters reveal a well-defined ridge–valley morphology characteristic of structurally controlled fold-and-thrust mountain belts.

Hydrological analyses further emphasize the importance of geological structure in landscape evolution. The drainage network exhibits a predominantly dendritic to sub-dendritic organization, although local channel orientations reflect structural influences associated with folding and fracture systems. The distribution of drainage density highlights the concentration of fluvial dissection within valley systems and moderately sloping terrain, while the weak correlation between slope and drainage density indicates that channel development is governed by multiple interacting factors, including lithology, structure, and hydrological conditions.

Vegetation patterns provide an additional dimension to the geomorphological interpretation. The spatial distribution of NDVI demonstrates a close relationship between vegetation cover, topography, and environmental gradients. Forested mountain sectors generally correspond to elevated and structurally controlled terrain, whereas lower vegetation density characterizes valley floors, cultivated areas, and peripheral plains. These patterns illustrate the strong coupling between geomorphological processes and ecological dynamics within the massif.

The integrated results therefore suggest that the Belezma–Batna anticline represents a landscape in which tectonic inheritance continues to exert a dominant influence on topographic organization despite prolonged erosion. Differential erosion acting on formations of contrasting mechanical resistance has progressively enhanced the ridge–valley morphology while preserving the structural framework imposed by Alpine deformation. The resulting landscape reflects the long-term interaction between geological structure, fluvial processes, topographic gradients, and environmental controls.

Overall, the Belezma massif constitutes a representative example of a structurally controlled mountain environment in northeastern Algeria, where tectonic structure, lithological variability, drainage organization, and vegetation distribution interact to shape a complex geomorphological system.

Conclusions

This study applied an integrated geomorphometric and remote sensing approach to investigate terrain morphology, drainage organization, and vegetation dynamics within the Belezma–Batna anticline of northeastern Algeria. Using SRTM-derived topographic data, HydroSHEDS hydrological information, and Sentinel-2 multispectral imagery, several morphometric and environmental indicators were analyzed to better understand the relationships between geological structure, surface processes, and landscape organization

The Digital Elevation Model revealed a strongly structured mountainous landscape dominated by an elongated ENE–WSW ridge system corresponding to the axis of the Belezma–Batna anticline. Elevation and slope analyses highlight a pronounced topographic contrast between the central ridge, characterized by steep slopes and high relief, and the surrounding piedmont areas where terrain becomes progressively smoother.

Morphometric parameters, including slope, Topographic Position Index (TPI), terrain curvature, and Relative Elevation Index (REI), confirm the well-developed ridge–valley organization of the massif and demonstrate the strong influence of geological structure and lithological contrasts on terrain morphology. Resistant carbonate formations form prominent structural ridges, whereas weaker marl-rich and siliciclastic units preferentially occupy valleys and structural depressions.

Hydrological analyses further emphasize the structural control exerted by the anticline on drainage organization. The extracted drainage network exhibits a predominantly dendritic to sub-dendritic pattern, while local channel orientations reflect the influence of structural lineaments and ridge alignment. Spatial variations in drainage density indicate heterogeneous fluvial dissection across the massif, with dense drainage networks concentrated within dissected valley systems and moderately sloping terrain. The weak negative correlation between slope and drainage density demonstrates that drainage development is controlled by multiple interacting factors, including lithology, structure, and hydrological conditions.

The Relative Elevation Index (REI) highlights the spatial organization of topography across the massif and clearly distinguishes elevated ridge systems from valley bottoms and peripheral low-relief sectors. Together with the DEM, TPI, and drainage analyses, the REI results demonstrate the close correspondence between topographic organization and geological structure.

Vegetation distribution derived from NDVI analysis reveals a strong relationship between vegetation cover, topography, and environmental gradients. Higher NDVI values are predominantly associated with forested mountainous sectors, whereas lower values characterize valley floors, cultivated lands, and peripheral plains. These patterns indicate that terrain morphology and hydrological conditions play a major role in controlling vegetation distribution across the massif.

Overall, the results demonstrate that the geomorphology of the Belezma–Batna anticline is governed by the interaction of tectonic structure, lithological resistance, fluvial erosion, and eco-hydrological processes. The integrated use of DEM-derived morphometric parameters, hydrological indicators, and satellite-derived vegetation indices provides an effective framework for investigating structurally controlled mountain landscapes.

This study contributes to a better understanding of geomorphological processes within the Pre-Atlasic domain of northeastern Algeria and highlights the potential of remote sensing, GIS, and cloud-based geospatial analysis platforms for regional geomorphological and morphotectonic investigations in semi-arid mountain environments.

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