ASSESSMENT OF ACTIVE TECTONICS FROM ALTERITES AND GEOMORPHIC INDICES IN A PART OF THE CRYSTALLOPHYLLIAN BASEMENT OF GRANDE KABYLIE (NORTHERN ALGERIA), IMPACT ON LANDSLIDES

Mohamed KACIMI[1*], Chaouki BENABBAS[2], & Nabil MANCHAR[3]

[1]*Department of Geology Sciences, Constantine 1. Frères Mentouri university, Campus Zouaghi Slimane, Constantine 25000, Algeria; kacimi.mohamed@umc.edu.dz*
[2]*Territory Planning Research Center (CRAT), Campus Zouaghi Slimane, Constantine 25000, Algeria; chaoukibenabbas03@gmail.com*
[3]*Department of Geology Sciences, University of Larbi Ben M'hidi - Oum El Bouaghi 04000, Algeria; manchar.nabil@univ-oeb.dz*
*Corresponding author: kacimi.mohamed@umc.edu.dz

Abstract: The evaluation of active tectonics in a crystallophyllian basement context is of scientific interest because these terrains record polyphase deformations and exhibit some of the most complex structures that can be observed. In Grande Kabylie, an integral part of the internal domain of the Maghrebides chain, the initial structural anisotropy of the basement formations (schistosity and foliation) is intersected by other discontinuities of tectonics origin, and their geometry is strongly affected by the regional geological heritage. Neotectonics are constantly modifying the relief of the terrain, causing changes in the organization and hierarchy of the hydrographic network and in the geomorphological evolution of the region. The tectonics processes resulting from the convergence of the African and Eurasian plates generate active deformations causing variable uplifts in the relief. The crystallophyllian formations in the study area are also exposed to intense weathering and natural hazards (landslides and floods). We therefore present a new approach to assessing active tectonics in anisotropic metamorphic terrain. It consists of correlating alterites (alloterites and isalterites) and the relative tectonic activity index (Iat) derived from geomorphic indices, namely the basin shape index (Bs), the hypsometric integral (Hi), the stream length gradient (SL), the mountain front sinuosity (Smf), the basin asymmetry factor (Af) and the valley floor width to valley height ratio (Vf). The results obtained from the multi-criteria analysis of these indices using GIS and the correlation with alterites and field surveys corroborate the values of the relative tectonic activity index (Iat) obtained, thus validating the usefulness of the method as a tool for assessing neotectonics.

Keywords: Grande Kabylie, Ain El Hammam, Alterites, Isalterites, Alloterites, Maghrebides, Geomorphic indices.

1. INTRODUCTION

The peri-Mediterranean Alpine orogen comprises two branches in the western Mediterranean: the Betic Cordillera and the Maghrebides coastal range (Durand-Delga, 1969). These two branches meet in the west to form the Gibraltar Arc, while in the east, the Maghrebides chain extend to Calabria to form the Sicilian-Calabrian Arc. The Maghrebides orogenic structure is the result of the structuring of the Maghreb basin and its margins, which were located between the European and African continental margins.

The Algerian margin, initially formed as a passive margin in the Cenozoic era, was subsequently affected by collision processes between the Eurasian and African plates. This region is one of the most active areas in the western Mediterranean basin in terms of tectonics deformation and seismic activity. Earthquakes mainly linked to compression mechanisms (Nocquet & Calais, 2004) have repeatedly generated tsunamis, such as those of Djidjelli in 1856 (Yelles-Chaouche et al., 2009) and Boumerdès in 2003 (Sahal et al., 2009). These seismotectonics events highlight both the high

geodynamic potential of this continental margin and its exposure to multiple hazards.

Since the Middle Miocene, the convergence of the African and Eurasian plates has continued, with a current shortening rate of 5 mm/year (Argus et al., 1989). Geophysical investigations and data collection from the new Algerian seismic network, consisting of 80 digital stations mainly distributed in northern Algeria, have revealed blind, seismically active faults and mapped the focal mechanisms of the main earthquakes (Mw > 5.0) from 2006 to 2020 (Yelles-Chaouche et al., 2022), probably related to convergence. Tectonics movements during the Tertiary and Neotectonics periods played a major role in the formation of the relief as observed today. The changes observed in the mountainous relief in tectonically active regions, including Grande Kabylie, are probably due to tectonics uplift, erosion processes, and weathering, which in some places has led to the formation of alterites.

Tectonic events that occurred in the past can be deduced through geomorphological analysis of hydrographic networks (Silva et al., 2003). Thus, analysis of the hydrographic network will provide data on the tectonics activity involved in the evolution of the relief. Neotectonics activity linked to the continental uplift of the Grande Kabylie basement, associated with the geodynamic evolution of the Maghrebides mountain range, is characterized by abnormal contacts along the edges (Saadallah, 1992), a young, fragmented relief, steep-sided rivers, broken or undulating valley lines, and steep slopes. The study area, which is part of the Haut-Sébaou watershed, is prone to earthquakes, weathering, slope instability, and active landslides.

Slopes in Grande Kabylie are experiencing landslides of varying severity; some have caused serious damage to infrastructure, endangering the lives of local populations. The landslide at Aïn El Hammam, which covers a large area (more than 24 ha), has attracted the most attention since its reactivation in 2009, as it affects the heavily urbanized town of Aïn El Hammam, located 50 km southeast of the capital of the wilaya of Tizi-Ouzou, and continues to evolve to this day. The geological and geotechnical characterization and field investigations carried out to date have not clarified the causes that led to its onset or the factors influencing its movement. Highlighting the role of neotectonics and weathering may help to better understand the rupture phenomena that caused the movement and which may be found in many other places in the basement of Grande Kabylie.

Geomorphic and morphometric indices are essential indicators in the study of deformation processes and are widely used as a characterization

tool to distinguish active areas (Keller & Pinter, 2002; Chen et al., 2003; Topal, 2018). They offer a valid method for identifying, describing, and evaluating the evolution of landforms in relation to active tectonics, as evidenced by numerous studies (Ramirez-Herrera, 1998; El Hamdouni et al., 2008; Anand & Pradhan, 2017; Cheng et al., 2018; Sharma et al., 2018; Anand et al., 2019; Manchar et al., 2022). Their application has proven to be a decisive tool in defining the deformation process.

This study, which complements previous research, makes a significant contribution to the recognition of fault zones that may have been responsible for active tectonics, the high potential for the formation of alterites, and the identification of areas susceptible to gravitational movements. Although these elements play an important role in landscape dynamics, the relationship between neotectonics, alterites, and gravitational movements has been little developed. Our objective is to propose an integrated approach to improve the detection of slope failure thresholds. This approach is based on the correlative analysis of geomorphic indices, the development of alterites, active tectonics, and landslides.

Our methodology is based on a multi-criteria analysis carried out in a GIS environment, applied to part of the Haut-Sébaou watershed in Grande Kabylie. This approach includes the delimitation of sub-basins and the systematic calculation of geomorphic indices, in particular the stream length gradient (SL), the basin shape index (Bs), the basin asymmetry factor (Af), the hypsometric integral (Hi), as well as hypsometric curves, the mountain front sinuosity (Smf), and the valley floor width to valley height ratio (Vf). Analysis of these various indices enables the validation and interpretation of the active tectonic index (Iat) by incorporating the description of weathering profiles, field investigations, including the identification of unknown faults and recorded ground movements.

2. GENERAL SETTING

The study area (Figure 1a-b) in northern Algeria (longitude 4°14'5" E to 4°23'22" E; and latitude 36°28'49" N to 36°38'45" N, WGS 84, UTM 31N) is located within the crystallophyllian massif of Grande Kabylie, which belongs to the internal domain of the Maghrebide Alpine chain. This region is a structural component of Alpine orogeny, resulting from the closure of the Tethys domain during the Cenozoic era (Durand-Delga, 1969; Frizon de Lamotte et al., 2008). In this region, the geological heritage, topography, climatology, and moderate seismicity form a complex system that makes it
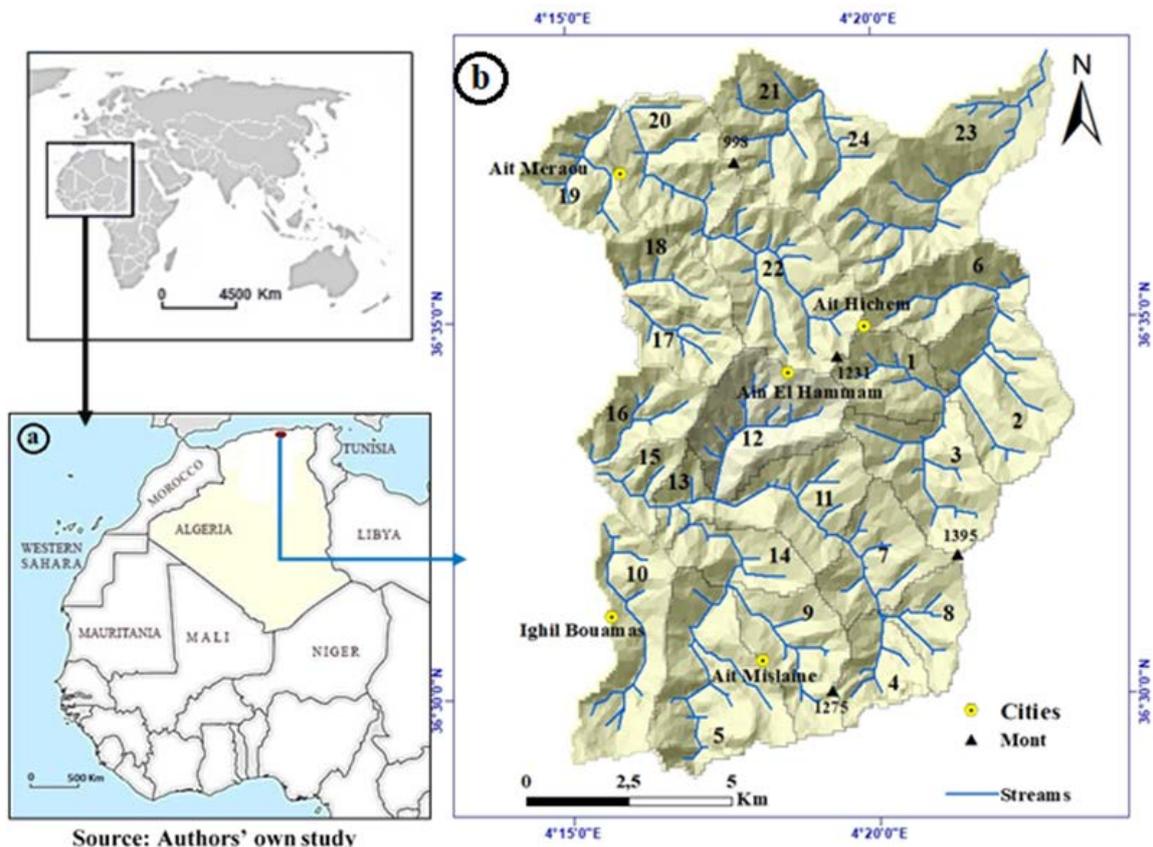
Figure 1. a. Geographic location of the study area; b. The 24 sub-basins of the Haut-Sébaou basin.

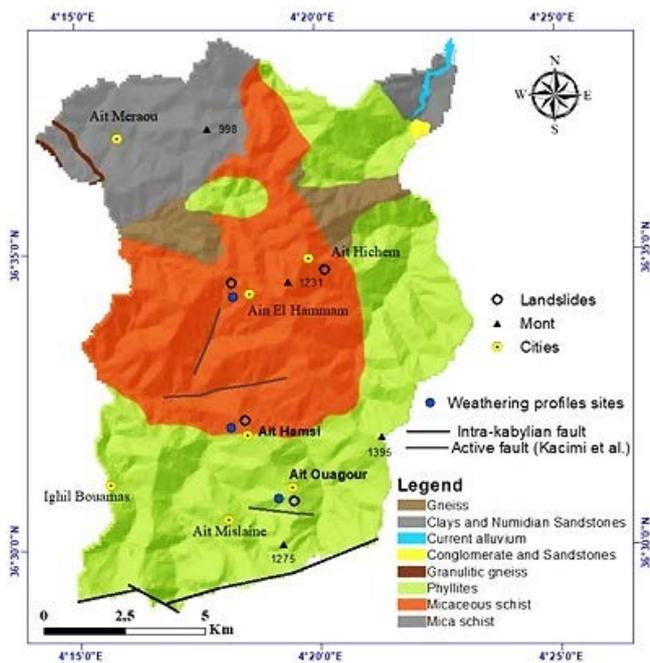vulnerable to landslides, as evidenced by the localities of Aïn El Hammam, Tigzirt, and Azzazga.

The terrain is rugged, with altitudes ranging from 400 to 1450 meters. Most of the area is dominated by slopes greater than 25 % (52.5 % of the total area). The study area is drained by a fairly dense hydrographic network, including Oued Djemaa, Acif El Hammam, and Oued Aouama, which are the main watercourses. The climate is Mediterranean, characterized by two alternating seasons, one cold and rainy and the other dry and hot.

Grande Kabylie consists of metamorphic formations affected by geological events extending from the Cretaceous to the Lower Miocene (from -80 to -20 Ma), to which were added those related to the extension that led to the formation of the Mediterranean Sea (from -20 to -10 Ma), as well as the effects of current compression, which correspond to the inversion period, from -10 Ma to the present. These geological events are linked to the convergence of two large tectonic plates, namely Africa to the south and Eurasia to the north. The driving force behind this dynamic is the opening of the Atlantic (Saadallah, 1992).

Structurally, the study area is characterized by an organization into three major units, bounded by regional-scale tectonic faults (Saadallah, 1992).

Eastern Grande Kabylie, whose structural boundaries are defined to the east by the Souama fault and to the west by the Oued Aïssi fault. The Sidi Ali Bou Nab (SABN) massif, whose structure is controlled by a west-northwest-dipping fault zone. Central and Western Grande Kabylie lies between the Oued Aïssi fault and the overlapping contact to the south of the SABN massif. This structural subdivision highlights the tectonic heterogeneity of the region, resulting from complex geodynamic processes.

The metamorphic formations in the study area are (Figure 2) interpreted as an ancient gneissic basement covered by a discordant schistose cover (Bossiere, 1978, 1980) and subsequently by a stack of tectonic-metamorphic units (Gani, 1988; Saadallah, 1992). The tectonic-metamorphic stack, from bottom to top, consists of: 1) para-gneisses with mineral marbles at the base and underlying lower eyed gneisses forming the ductile base; 2) the Sidi Ali Bou Nab (SABN) nappe consisting of granite with its cataclastic extrusion in the para-gneisses; 3) mica schists with underlying upper eyed gneisses; 4) satin schists; and 5) finally, granites and aplopegmatites cutting across virtually the entire tectonometamorphic pile. More recently, it has been described as a metamorphic core complex (MCC) (Saadallah & Caby, 1996).

Figure 2. Geological map, main structure of the study area and sites of alteration profiles.
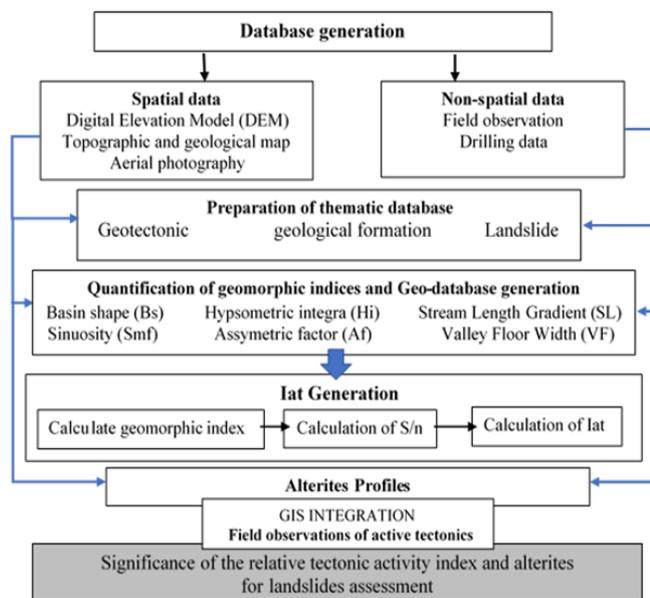
Source: Authors' own study

Figure 3. Methodological flow chart of the adopted approach.

3. MATERIAL AND METHODS

3.1. Data sources

The study area located in Grande Kabylie is part of the large Haut-Sébaou watershed. Topographic maps at a scale of 1/25,000, aerial photos at a scale of 1/20,000, and a digital elevation model (SRTM/DEM) with a spatial resolution of 30 m were used to extract the stream network (Figure 1b)

and calculate geomorphic indices. Geological maps at a scale of 1/50,000 were consulted, including Tazmalt nᵒ. 67, Azeffoun-Azazga nᵒ. 9/24 and, in particular Fort National nᵒ. 45, for the precise identification of lithological units and preliminary geological analysis. Field investigations and aerial photo, as well as satellite imagery (ETM+ Landsat 8 data), provided significant information for the structural reconnaissance of the study area.

ArcGIS 10.7.1 software was used to generate and process the geodatabase. The hydrographic network was extracted using water flow determination algorithms, and sub-basins were delineated. As a result, twenty-four sub-basins were identified (Figure 1b, Table 1). The adopted approach is summarized in the methodological flowchart. (Figure 3).

3.2. Weathering profiles

Weathering profiles are often studied in geological, hydrological, and geotechnical projects. However, their relationship with active tectonics processes remains poorly documented in scientific literature, particularly in northern Algeria. Two sites located in the study region with natural and anthropogenic escarpments were selected as reference sites for this study, Aïn El Hammam and Aït Ouagour, to which a third site (Aït Hamsi) was added for comparison purposes (Figure 2). This methodological choice was based on the existence of continuous outcrops allowing observation of the complete succession of altitudinal horizons. For the Aïn El Hammam and Aït Ouagour sites, a systematic stratified sampling campaign was carried out, covering all the different weathered horizons, supplemented by detailed visual descriptions and laboratory analyses, including grain size distribution, X-ray fluorescence (XRF), and X-ray diffraction (XRD). With regard to the Aït Hamsi site, the different horizons were identified by analogy with the first two. The Aïn El Hammam site was the subject of a special investigation using deep core sampling, initially carried out to study a landslide. The cores obtained were included in the analytical protocol. The data enabled complete weathering profiles to be established, summarizing the various characteristics. The aim is to compare the different weathering profiles and correlate them with the tectonic activity index (Iat) obtained.

3.3. Calculation of geomorphic indices

The six geomorphic indices, quantitative tools used in the assessment of active tectonics and the analysis of geomorphological processes, were

calculated to characterize the 24 sub-basins of the study area. The values obtained for each index (Table 1) were classified according to categories predefined in the scientific literature, particularly those adopted by Anand & Pradhan (2019). A weighted average of the classes assigned to each sub-basin was then calculated to determine the relative tectonic activity index (Iat). This index allows the quantification and classification of tectonics activity levels (very high, high, moderate, and low) within the study area. A correlative analysis was conducted to assess the likely relationship between variations in the Iat and the occurrence of landslides, thereby contributing to a better understanding of the interactions between tectonics dynamics and gravity hazards. The six indices are described in the Table 1.

3.3.1. The basin shape index (Bs)

The shape of basins tends to become more elongated in tectonically active areas. High Bs values are generally associated with elongated basins, while low values indicate basins that tend to evolve towards a circular shape over time (Bull & McFadden, 1977). Bs is calculated using the equation:

$$Bs = Bj / Bw \quad (1)$$

where: Bj is the length between the sources and the mouth of the basin, Bw is the width of the basin measured at its widest point (Ramirez-Herrera, 1998).

3.3.2. The hypsometric integral (Hi)

The hypsometric integral is an index that characterizes the distribution of elevation in any area of a landscape (Strahler, 1952; Khavari et al., 2010). The integral is calculated independently of the basin area and is a specific index expressing the volume of the basin that has not been eroded, in the sense that high values may suggest a younger landscape, probably shaped by tectonics (El Hamdouni et al. 2008). The integral and hypsometric curves are essential for understanding the development of watersheds controlled by erosion and material deposition. Hi is calculated using the equation (Pike & Wilson, 1971; Keller & Pinter, 2002):

$$Hi = (\text{elevation}_{avg} - \text{elevation}_{min}) / (\text{elevation}_{max} - \text{elevation}_{min}) \quad (2)$$

where: $Elev_{avg}$, $Elev_{min}$, and $Elev_{max}$ are the average, minimum, and maximum elevations.

Table 1. Values and classifications of Bs, Hi, SL, Smf, Af, Vf, and Iat.

No.	Name	Geomorphic Indices												S/n	Iat	Class
		Bs		Hi		Sl		Smf		Af		Vf				
		Value	Class	Value	Class	Value	Class	Value	Class	Value	Class	Value	Class			
1	Ait Hichem	1,57	2	0,54	1	575	1	1,14	1	17,6	2	0,12	1	1,33	1,33	1
2	Aouama	1,89	2	0,47	1	198	3	1,11	1	30,2	1	0,13	1	1,50	1,50	2
3	Igoures	1,98	2	0,47	1	458	1	1,2	2	11,24	2	0,11	1	1,50	1,50	2
4	Akaoudj	1,16	2	0,36	2	393	2	1,21	2	11,92	2	0,12	1	1,83	1,83	2
5	Acif Hammam	1,36	2	0,41	1	138	3	1,17	2	5,46	3	0,40	2	2,17	2,17	3
6	Ait Haroun	2,14	2	0,46	1	365	2	1,14	1	1,49	3	0,12	1	1,67	1,67	2
7	Ait Abdellah	1,25	2	0,38	2	93	3	1,23	2	16,93	2	0,18	1	2,17	2,17	3
8	Ouardja	1,17	3	0,35	2	324	2	1,13	1	3,6	3	0,25	2	2,17	2,17	3
9	Ait Ouagour	1,95	2	0,37	2	426	1	1,14	1	11,54	2	0,22	1	1,50	1,50	2
10	Ighil Bouamas	2,06	2	0,34	2	334	2	1,06	1	0,29	3	0,26	2	2,00	2,00	2
11	Oued Djemaa	1,62	2	0,39	2	162	3	1,12	1	6,91	3	0,19	1	2,00	2,00	2
12	Ain El Hammam	2,71	1	0,50	1	606	1	1,05	1	18,73	1	0,17	1	1,00	1,00	1
13	Ouait Slid	2,00	2	0,33	2	37	3	1,08	1	1,94	3	0,26	2	2,17	2,17	3
14	Ait Hamsi	1,96	2	0,39	2	81	3	1,16	2	6,39	3	0,17	1	2,17	2,17	3
15	Souk El Had	1,27	2	0,34	2	47	3	1,19	2	11,96	2	0,39	2	2,17	2,17	3
16	Ighzer Tazerout	1,36	2	0,50	1	486	1	1,2	2	1,92	3	0,12	1	1,67	1,67	2
17	El Korne	1,73	2	0,53	1	478	1	1,26	2	10,37	2	0,17	1	1,67	1,67	2
18	Azro Kollal	1,50	2	0,51	1	448	1	1,18	2	8,66	2	0,15	1	1,50	1,50	2
19	Ighil Tigmounine	1,35	2	0,61	1	246	2	1,18	2	3,77	3	0,49	3	2,17	2,17	3
20	Ait Meraou	1,30	2	0,52	1	249	2	1,19	2	5,35	3	0,16	1	1,83	1,83	2
21	Ait Boutchour	1,18	3	0,55	1	258	2	1,28	2	26,22	1	0,18	1	1,67	1,67	2
22	Bouaggache	1,43	2	0,49	1	447	1	1,19	2	3,29	3	0,21	1	1,67	1,67	2
23	Lemkharda	2,00	2	0,44	1	510	1	1,16	2	6,1	3	0,19	1	1,67	1,67	2
24	Ait Ahmed	1,11	3	0,51	1	406	1	1,21	2	7,7	2	0,25	2	1,83	1,83	2

Source: Authors' own study

3.3.3. The stream length gradient (SL)

The stream length gradient index is based on a quantitative approach linked to erosion and deposition processes (Hack, 1973). Streams typically have longitudinally concave profiles (Snow & Slingerland, 1987). This index allows estimates of slope variation along a stream, which can reveal information about the geomorphological processes involved and tectonics activity. Abnormally high SL values reflect tectonic activity (Keller, 1986). The SL value is determined by the equation:

$$SL = (\Delta H / \Delta L) \times L \quad (3)$$

where: $\Delta H / \Delta L$ is the slope or gradient of the channel section, and L is the total length of the channel.

3.3.4. The mountain front sinuosity (Smf)

The Smf expresses the balance between the erosion processes that modify a mountain front, making it more sinuous through the lateral and frontal action of watercourses, and the active vertical tectonics that favor the formation of straight mountain fronts, often correlated with active faults or folds. The Smf index is determined from topographic maps and aerial photographs. Smf values tend towards 1 for tectonically active fronts, while Smf increases as the uplift rate decreases and erosion processes cause the front to become increasingly sinuous (Bull, 1978; Rockwell et al., 1985; Keller, 1986). Smf is calculated using the equation:

$$Smf = Lmf / Ls \quad (4)$$

where: Lmf has been defined as the planimetric length of a mountain front, while Ls is the length of a mountain front measured along a straight line.

3.3.5. The basin asymmetry factor (Af)

It is an expressive indicator for assessing the tectonics dip of a basin. When the Af value deviates from 50 (either higher or lower), this may indicate a dip in the basin caused by tectonic activity or by differential erosion influenced by the geological structure (Hare & Gardner, 1985). The AF is calculated using the equation:

$$Af = (Ar / At) \times 100 \quad (5)$$

where: Ar represents the area of the right bank of the main channel, looking downstream, and At corresponds to the total area of the catchment basin.

3.3.6. The valley floor width to valley height ratio

The valley floor (Vf) is defined as the ratio between the width of the valley floor and the height of the valley. It allows U-shaped valleys to be distinguished from V-shaped valleys (Bull & McFadden, 1977; Bull, 1978). This ratio is sensitive to tectonics uplift movements. The Vf is calculated using the equation:

$$Vf = 2Vfw / [(Eld - Esc) + (Erd - Esc)] \quad (6)$$

where: Vfw is the width of the valley floor, while Eld and Erd represent the elevation of the left and right ridges of the valley, respectively. However, Esc represents the average altitude of the valley floor.

4. RESULTS

4.1. Weathering profiles

The substrates consist of micaceous schist in the sub-basins of Aïn El Hammam, Aït Hamsi and satiny schist (phyllite) in that of Aït Ouagour (Figure 2). The parageneses of these unaltered rocks, determined by microscope and X-ray diffraction, have a simple mineralogical composition: muscovite + albite + quartz for the first sites, and quartz (in dominant proportion) + biotite + chlorite for the second.

Field descriptions for the two sectors, Aïn El Hammam and Aït Ouagour, in the study area, corroborated by the analysis of samples from boreholes, have identified a succession of perfectly distinct alterogenic horizons, observable both at outcrops and in borehole cores, with a clearly differentiated organization from top to bottom: the alterites horizon, subdivided into two sub-horizons, the alloterites and the isalterites, the fractured and fissured horizon, and the fractured substratum.

Alterites is a specific part of the weathering profile that shows where the rock has been most weathered, forming loose materials such as clay, sand, or grit. There are alloterites (weathering with loss of volume and texture of the parent rock) and isalterites (isovolumetric weathering, with preservation of texture). Weathering profiles are represented as vertical sections, comprising both the weathered zones (alterites) and the transition zone between them and the fractured substratum. (Figures 4 and 5).

4.2. Geomorphic indices

The calculation of geomorphic indices aims to highlight active tectonics and its influence on deformation processes (Rockwell et al., 1985; Silva et al., 2003; El Hamdouni et al., 2008). The calculation of the six indices is applied to the 24 sub-basins identified in the Haut-Sébaou in Grande Kabylie. The intervals defined by Anand & Pradhan

(2019) during the assessment of active tectonics in the Ganges basin were adopted to classify the values obtained (Table 1) in the study area due to the similar geological context consisting mainly of crystallophyllian rocks.
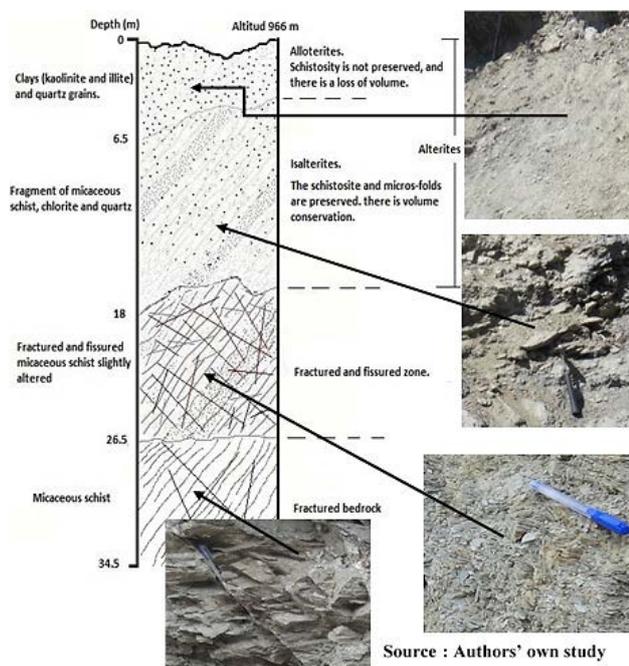

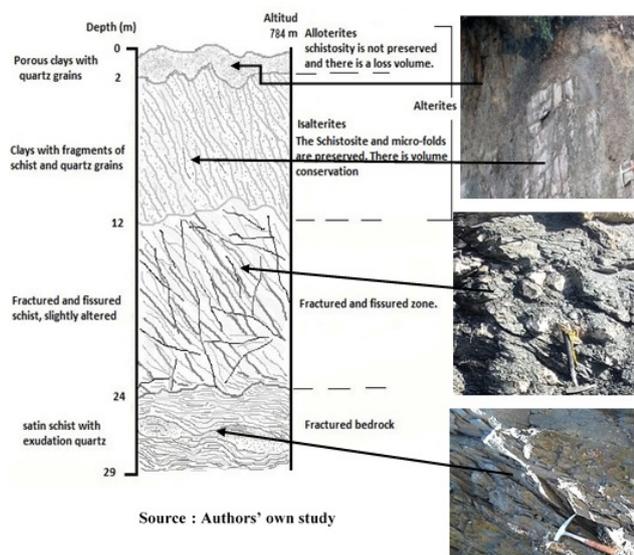Figure. 4. Weathering profile of Ain El Hammam in study area.

Figure. 5. Weathering profile of Ait Ouagour in study area.

4.2.1. The basin shape index (Bs)

An elongated, steep-sided basin is generally the result of a process of mountain front uplift associated with relatively intense tectonic activity. This unique morphology can be recognized by higher values of the Bs index (Ramirez-Herrera, 1998). Bs values are subdivided into three categories: class 1 ($\geq$ 2,30), class 2 (2,30-1,20) and class 3 (< 1,20). These classes reflect high, moderate and low tectonic activity, respectively. Bs was calculated for the 24 sub-basins in the study area. The values range from 1,11 to 2,71(Figure 6a) and the results are presented in Table 1. The majority of the sub-basins belong to class 2. Only one belongs to class 1 (Ain El Hammam no 12) and three sub-basins belong to class 3. (Figure 7a).

4.2.2. The hypsometric integral (Hi)

Hi values range from 0,33 to 0,61 (Table 1, Figure 6b). The highest Hi value was calculated for sub-basin no 19 (0,61), while the lowest value was found for sub-basin no 13 (0,33). The calculated values are compared to three classes defined by Anand & Pradhan (2019): class 1 ($\geq$ 0,40) represents convex hypsometric curves, class 2 (0,39-0,30) represents S shaped (concave-convex) hypsometric curves, and class 3 (< 0,30) represents concave hypsometric curves. These classes 1 to 3 represent the young, moderate, and mature stages of basin development, respectively. For the study area (Figure 7b), 15 sub-basins are class 1 with Hi values ranging from 0,46 to 0,61. Among these, sub-basins no 01, no 19 and no 21 are characterized by high values, 0,54 , 0,61 and 0,55, respectively. Nine sub-basins belong to class 2, with Hi values ranging from 0,33 to 0,39. The hypsometric curves of all sub-basins are plotted cumulatively, and the hypsometric integral is obtained with S shaped curves, and most of which are convex. (Figure 8).

4.2.3. The stream length gradient (SL)

The SL index values for the 24 sub-basins vary from 606 (no 12), the greatest, to 37 (no 13), the lowest (Figure 6c). Based on the recent research that suggested subdivisions, especially the one by Anand & Pradhan (2019), there are three groups of SL values: class 1 (>400), class 2 (400-200), and class 3 (<200). Class 1 has 10 sub-basins with SL values between 406 and 606, while class 2 has 7 sub-basins with SL values between 246 and 393. In class 3, there are further seven sub-basins with SL values between 37 and 198. Class 1 and 2 are the most expressed, which means that the region being studied mostly has steep to moderate relief (Figure 7c). Two of them, no 12 (Aïn El Hammam) and no 1 (Aït Hichem), stand out with respective values of 606 and 575.

4.2.4. The mountain front sinuosity (Smf)

The Smf (mountain front sinuosity index) is an indicator used to estimate whether a mountain front is regular or complex. A value close to 1 suggests a relatively straight mountain front that may be closely associated with active vertical tectonics. However, a more sinuous mountain front, which may be due to erosive processes, is recognized by a higher value of

the index. The Smf is divided into three categories: class 1 (< 1,16), class 2 (1,16-1,30) and class 3 (> 1,30) (Anand & Pradhan, 2019). The values of this index for the study area are below 1,30, ranging from 1,05 to 128 (Figure 6d). There are fifteen sub-basins in class 2 and nine sub-basins in class 1 (Figure 7d).

4.2.5. The basin asymmetry factor (Af)

For the 24 sub-basins in the study area, the asymmetry factors (AF) calculated classify sub-basin n° 02 as asymmetrical with the highest AF value (80,20), while n°10, with the lowest AF (50,29), is found to be a slightly asymmetrical sub-basin (Figure 6e). The difference between the observed value and the neutral value (50) expresses the calculation of the asymmetry factor in terms of absolute value. The FA-50 is assessed and classified into three categories (Anand & Pradhan, 2019), namely: class 1 (>18), class 2 (18-7) and class 3 (< 7). Class 1 includes sub-basins with values ranging from 18,73 to 30,20. It concerns n° 12, n° 21 and n° 02. Class 2 includes nine sub-basins with values ranging from 7,70 to 17,60. Class 3 includes twelve sub-basins with values ranging from 1,92 to 6,91 (Figure 7e).

4.2.6. The valley floor width to valley height ratio (Vf)

U-shaped valleys generally have high Vf values, while V-shaped valleys, which represent the early stage of development, have relatively low values (Silva et al., 2003). A significant number of valleys were selected to calculate the Vf values of the main watercourses in the study area. The latter is represented as a whole by a homogeneous geological context, dominated mainly by crystallophyllian bedrock. The values obtained (Figure 6f) range from a minimum of 0,11 (sub-basin n° 3) to a maximum of 0,49 (n° 19). The Vf values were divided into three classes, in accordance with the classification of Anand & Pradhan (2019) adopted in the same geological context: class 1 (<0,25), class 2 (0,25-0,40) and class 3 (>0,40). Of the 24 sub-basins studied, more than half (17) fall into class 1, while six belong to class 2 and only one to class 3 (Figure 7f).

4.3. The relative tectonic activity index (Iat)

Three classes of relative tectonic activity index (Iat) were identified from the study of 24 sub-basins by normalizing the different classes of geomorphic indices (S/n). The values obtained (Table 1) range from 1 to 2,17. Referring to the classification of El Hamdouni et al. (2008), among the 24 sub-basins, two sub-basins in class 1 (n° 1 and n° 12) show very high activity (S/n <1.5). Furthermore, 15 sub-basins in

class 2 are characterized by high activity (1.5 < S/n < 2). Finally, 7 sub-basins show moderate activity in class 3 (2 < S/n < 2.5) (Figure 9).

5. DISCUSSION

The evaluation and quantification of relative tectonics activity in a given region were carried out using geomorphic and morphometric indices (Bull & McFadden, 1977; Rockwell et al., 1985; Azor et al., 2002; El Hamdouni et al., 2008; Dehbozorgi et al., 2010), combined with linear, surface and relief parameters (Anand & Pradhan, 2019).

The main objective of this study is to analyze and evaluate active tectonics in the anisotropic crystallophyllian terrains of the study area. It also aims to decipher its impact on gravitational movements.

The initial structural anisotropy of the basement formations (schistosity and foliation) is intersected by other discontinuities of tectonic origin, and the geometry of these discontinuities is strongly affected by the regional geological heritage. Tectonics accidents are often influenced by this anisotropy, and faults may follow schistosity and/or foliation planes, making them difficult to distinguish in the field.

The evaluation of tectonics activity in a metamorphic basement is extremely fruitful, as it presents some of the most complex structures that can be observed.

The methodological approach is based on the use of geomorphic index evaluation results, the relative tectonic activity index (Iat) and the formation of alterites, supplemented by field observations.

5.1. Geomorphic indices

The calculation of geomorphic indices aims to highlight active tectonics and its influence on deformation processes.

5.1.1. Basin shape index

The basin shape index was interpreted to determine the influence of tectonics activity. The majority of the 20 sub-basins have a Bs > 1,2 (Figure 6a). This prevalence of class 2 (Figure 7a) indicates that most sub-basins have moderate symmetry, suggesting a tendency toward elongation, probably due to moderate tectonics processes.

They are distributed throughout the study area. Sub-basins with a shape index Bs > 2 are likely influenced by tectonics events. Three sub-basins located to the north and south stand out from the rest with values <1,20 (class 3), reflecting low tectonics activity. The highest value of 2,71 is found in the Ain
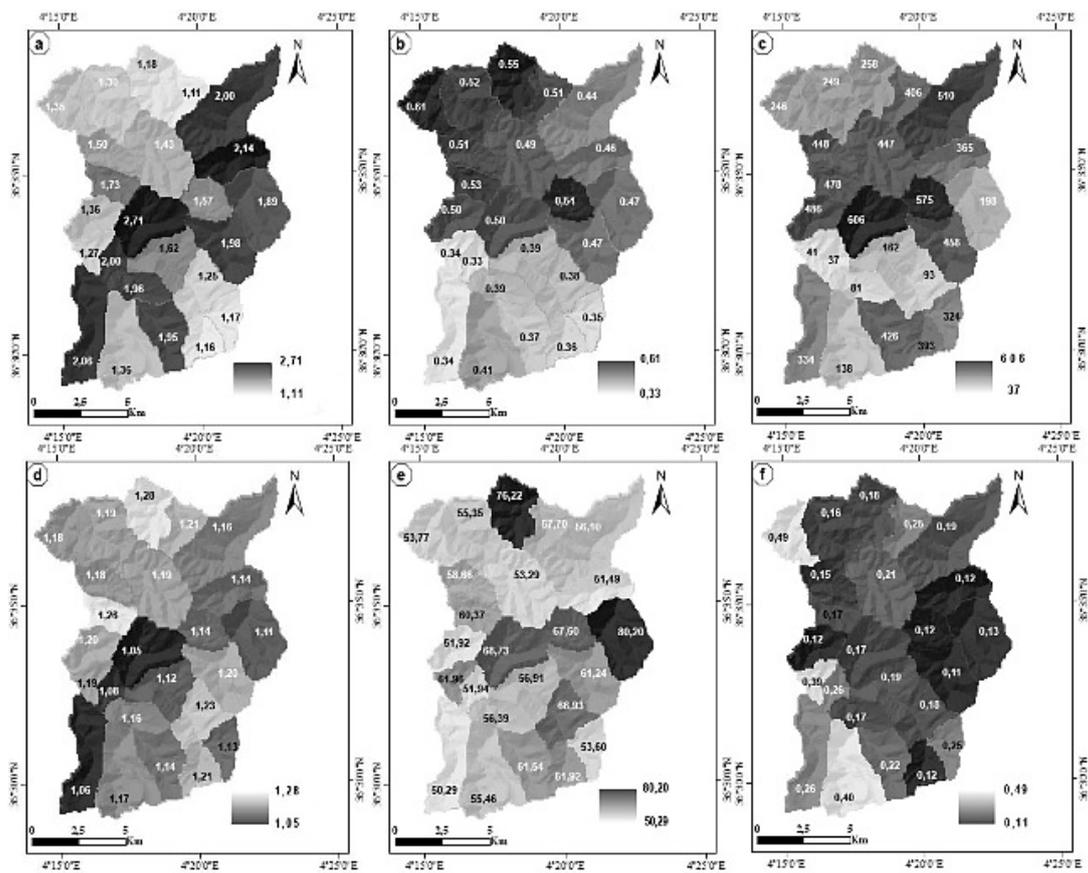
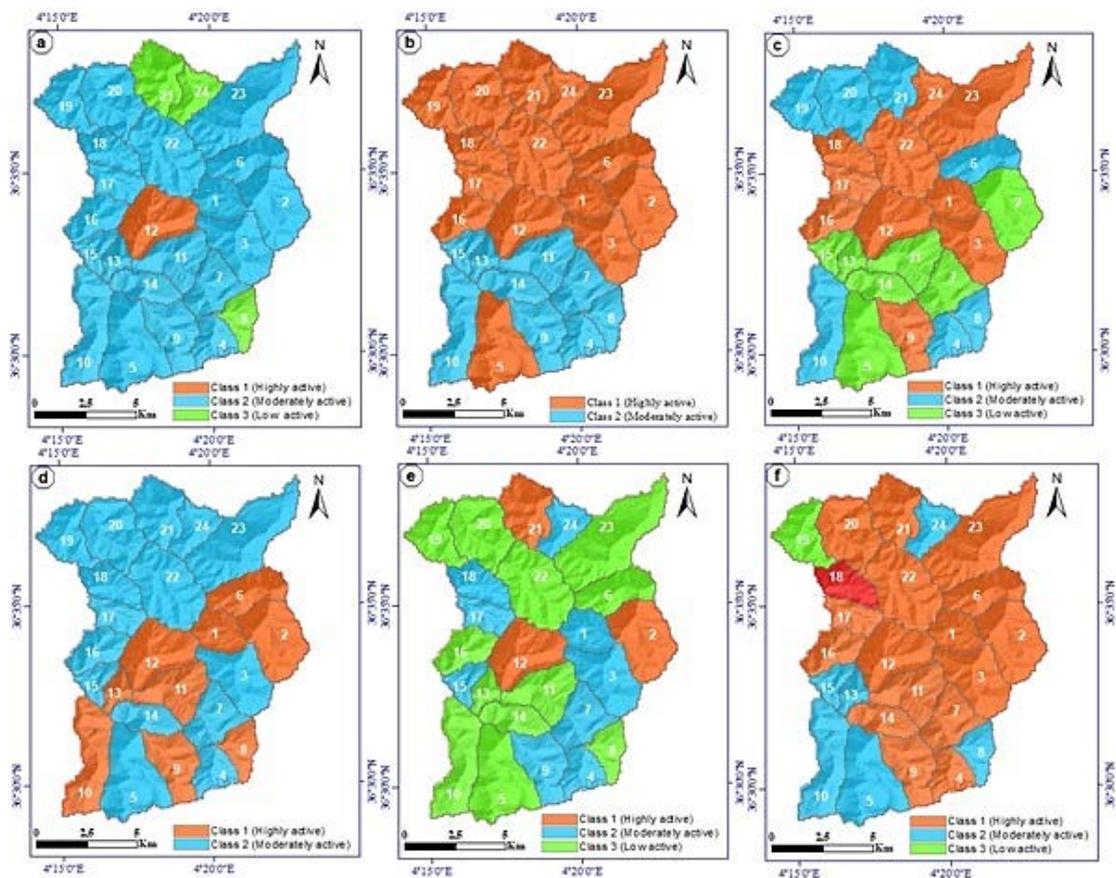Figure 6. Values of geomorphic indices: a. Bs; b. Hi; c. Sl; d. Smf; e. Af; f. Vf.

Figure 7. Classes of geomorphic indices: a. Bs; b. Hi; c. Sl; d. Smf; e. Af; f. Vf.

El Hammam sub-basin in the center, suggesting more intense tectonics activity.

5.1.2. The hypsometric integral (Hi) and hypsometric curves

The Hi values ranging from 0,33 to 0,61 in the 24 sub-basins studied (Figure 6b) reflect diversity in morphological characteristics. Class 1 sub-basins occupy the center and north of the study area, while class 2 sub-basins are generally limited to the southern part (Figure 7b). This distinction supports the existence of an active boundary in the center delimiting the young sub-basins (in the north) and the relatively young sub-basins (in the south). Convex hypsometric curves are dominant in the study area (Figure 8). Those in class 1 (Hi ≥ 40) have marked convex hypsometric curves, typical of young stages subject to active tectonics activity, and those in class 2 (0,33-0,69) have S shaped (convex-concave) hypsometric curves, associated with a moderate stage of relief development. These findings highlight the role of tectonics activity in the formation of the relief of the study area.
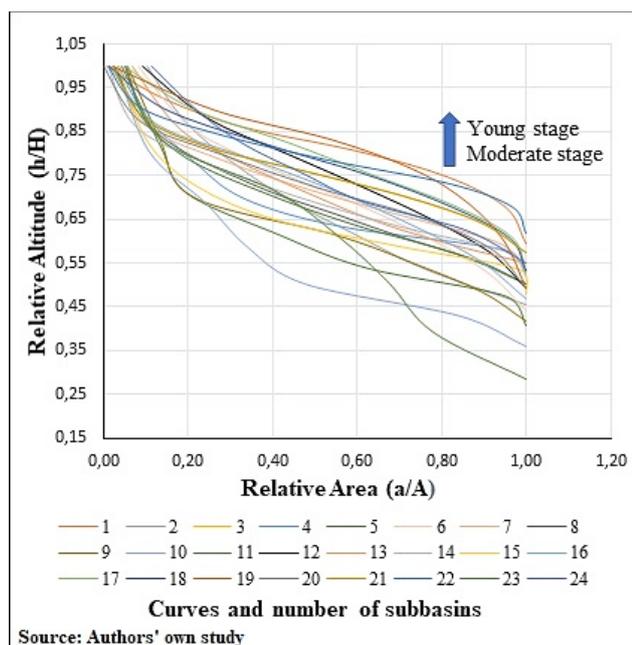

Figure 8. Hypsometry curves of subbasins from Haut-Sébaou. (A) is the total surface of the sub-basin, (a) is the surface area within the sub-basin above a given line of elevation (h), (H) is the highest elevation of the sub-basin.

5.1.3. The stream length gradient (SL)

For the study area, SL index values depend on changes in river slope and anomalies or deviations in the river profile that are related to tectonics. They are differentiated by non-tectonics factors such as lithological contrasts (since the more or less homogeneous geological substrate is represented by crystallophyllian formations), confluences, and anthropogenic interventions. The SL index was calculated for each sub-basin (Figure 6c), revealing a dominance of active and moderately active classes (Figure 7c). The study highlighted areas where high SL index values of class 1 indicated significant alignments, mainly in the center along the east-west direction, as well as in the adjacent sub-basins on the on the north side. In the southern part, sub-basin n° 9 stands out from the class 2 sub-basins with a high SL index value of 426. This distribution supports the presence of active tectonic processes in certain areas of the study region. Sub-basins n° 12 and n° 1 stand out with very high values (606 and 575).

5.1.4. The mountain front sinuosity (Smf)

The calculated Smf values (Figure 6d) reflect relatively straight and moderately sinuous mountain fronts, suggesting tectonics activity. Class 2 covers a fairly large area (Figure 7d). Among the Class 1 sub-basins, four have fronts oriented roughly NE-SW in the center of the study area. They delimit the north, which consists of Class 2 sub-basins, from the south, which includes Class 1 and Class 2 sub-basins. However, significant faults with this orientation are widespread in northern Algeria. The four Class 1 sub-basins could be located near active faults. The lowest value (1,05) associated with an active mountain front characterizes sub-basin n° 12 (Aïn El Hammam).

5.1.5. The asymmetry factor (Af)

A more pronounced tilt of a basin means that the AF is significantly greater than 50 and reflects the effect of active tectonics (Alipoor et al., 2011). The calculated asymmetry factors (AF) of the 24 sub-basins (Figure 6e) show significant variations in their degree of asymmetry. Half are class 3, nine are class 2, and three are class 1(Figure 7e). Sub-basin n° 02, with the highest AF value (80,20), stands out for its high asymmetry. In contrast, sub-basin n° 10 has the lowest AF (50,29), classifying it as slightly asymmetrical. Sub-basins n° 12 and n° 2 (class 1) with the moderately asymmetrical sub-basin n° 1 (class 2) form a group located in the center of the study area in an east-west direction. This direction coincides perfectly with that of the intra-Kabyle fault, which delimits the Kabyle basement formations from those of the Dorsale Kabyle to the south of the study area.

5.1.6. The valley floor width to valley height ratio (Vf)

Low Vf values, ranging from 0,11 to 0,22 (Figure 6f) are V-shaped valleys representing the early stage of development. They are categorized in class 1 and occupy a large space in the study area (17 sub-basins), particularly in the center (Figure 7f).

However, the wider valleys in class 2 (6 sub-basins) with values ranging from 0,25 to 0,40 are scattered, and class 3 (1 sub-basin) with a value of 0,49 is located in the north-west. The low Vf values indicate narrow, steep valleys that undergo more intense erosion processes, where active incision rates and tectonics uplifts are often observed. In the study area, these are accompanied in places by gravitational movements, as in the case of the Aïn El Hammam landslide (sub-basin nᵒ 12).

5.2. The weathering profiles and the relative tectonics activity index (Iat)

Analysis of weathering profiles in two sub-basins of the study area (Ain El Hammam and Ait Ouagour) (Figures 4 and 5) reveals that their substratum is intensely fractured, regardless of lithological differences. The presence of a deep fractured and fissured zone is indicative of tectonics deformation resulting from stresses that have affected the region. The depth of the alterites, exceeding 18 meters (Aïn El Hammam profile), as well as the intensification of alteration towards the upper horizons, are clear indicators of continuous tectonics exhumation, favored by active crustal dynamics.
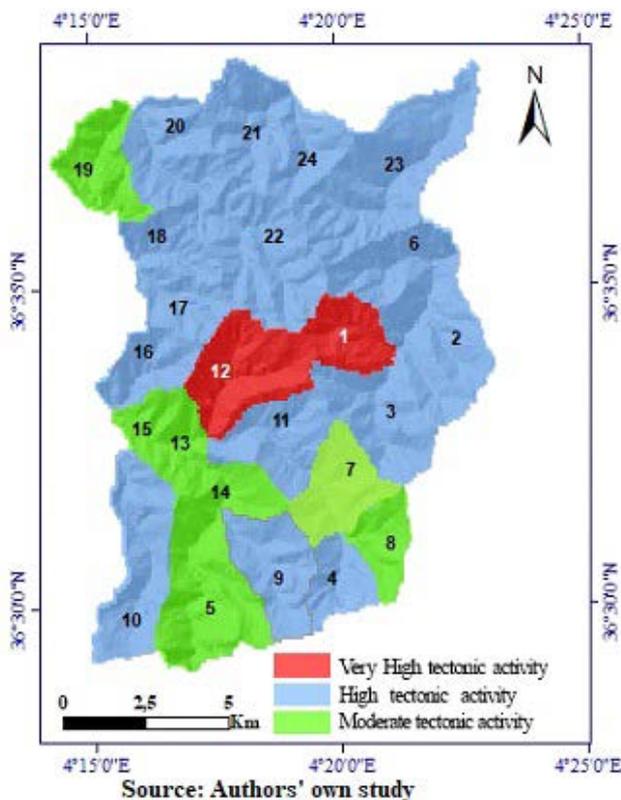

Figure 9. Relative tectonics activity indexes.

The presence of microfolds in the isalterites horizon attests to previous ductile deformation, followed by a more recent fracturing phase.

Furthermore, a clear correlation is observed between the thickness of the alloterites horizon and the tectonics activity index (Iat). This horizon is more developed, around 6.5 meters in the Aïn El Hammam sub-basin (Iat class 1), and shows a significant reduction in the Aït Ouagour sub-basin of approximately 2 meters in thickness (Iat class 2). However, in a sub-basin with a Class 3 Iat (Aït Hamsi for example), this horizon becomes residual, with a very reduced thickness of less than 0.5 meters.

Metamorphic rocks, which are generally not very permeable due to their compactness, become significantly more reactive as they rise toward surface conditions. This process allows for increased mechanical disintegration, facilitates the infiltration of meteoric water, and amplifies chemical weathering reactions. In the absence of active tectonics, these rocks would remain deep underground, isolated from surface agents (erosion, weathering). In the study area, the genesis of spatially heterogeneous thick alterites is probably the result of rapid differential uplifts, gradually exposing fresh rock to conditions conducive to weathering and increasing erosion rates. Without this dynamic, erosion would be more uniform and less effective. Furthermore, the development of fractures in all weathering horizons could be attributed to uplift mechanisms in a collision context, linked to the known convergence of the African and Eurasian plates. This highlights the fundamental role of active tectonics in the structuring of alterites in Grande Kabylie. Careful observation has also revealed that the fractures in the substratum are open and not filled with secondary minerals, a strong indicator of recent tectonic activity. Tectonics has played a fundamental role in the formation of alterites by controlling both the depth and intensity of the weathering processes.

Active tectonic dynamics characterized by spatial variation are highlighted by analysis of the relative tectonics activity index (Iat) for the study area. High to very high activity classes cover most of the 24 sub-basins. Among these, two class 1 sub-basins (Aïn El Hammam and Aït Hichem) are probably associated with active faults or recent tectonic movements. In one of these sub-basins, a major landslide has been reported, confirming the geomorphological instability induced by this tectonics activity.

5.3. Field observations of active tectonics

It is essential to determine the extent to which the active tectonic index (Iat), assessed by geomorphic indices and alterites profiles, is consistent with field observations of active tectonics.

Vertical deformation rates due to tectonics activity in the basement of Grande Kabylie remain largely unknown due to the absence of Quaternary formations, with the exception of alluvial terraces. However, there is ample evidence of vertical displacement, but due to the lack of a chronology of Quaternary units, the interpretation of active tectonics has proven complex.

Field investigations conducted in the study area, particularly in its central portion, have revealed several morphostructural indicators attesting to significant neotectonic activity. In the Aïn El Hammam sector (sub-basin 12), analysis of outcrops revealed the presence of an undulating and striated fault mirror, characteristic of oblique reverse fault with left-hand strike-slip (Figure 10 a).

In addition, linear escarpments cutting across the surrounding relief were observed and interpreted as probable evidence of recent tectonic reactivation. Observations also showed that the Oued Djemaa, which initially ran south-north, undergoes a sudden deviation to the east-west, forming a sharp angle of approximately 90°. This geometric anomaly could be linked to active tectonic stresses.

In addition, the presence of closely interlocking alluvial terraces (Figure 10 b), developed exclusively on the right bank of the Oued Djemaa and absent on the opposite bank, suggests differential uplift. This phenomenon could result either from recent fault reactivation or from folding affecting the underlying metamorphic substratum, whose structural anisotropy makes it particularly sensitive to crustal deformation.

The asymmetrical morphology of the Oued Djemaa, characterized in particular by a fluvial overhang (Figure 10c), suggests active tectonic control rather than purely erosive fluvial dynamics. The preservation of alluvial deposits in a stepped arrangement indicates accelerated incision, likely induced by successive tectonic uplifts.

In addition, the evidence of a reverse fault (Figure 10d), cutting across an alluvial terrace level, provides irrefutable evidence of recent tectonics deformation. The decimetric vertical rejection of this compressive structure explains the differential elevation of the banks of the Oued Djemaa.

Field observations provide direct evidence of active tectonics, consistent with moderate to very high values of the tectonic activity index (Iat), reflecting differential deformation within the region. These results demonstrate that the region, although composed of ancient metamorphic rocks, has been affected by recent active deformation, probably in response to current crustal stresses related to the convergence of the African and Eurasian plates.
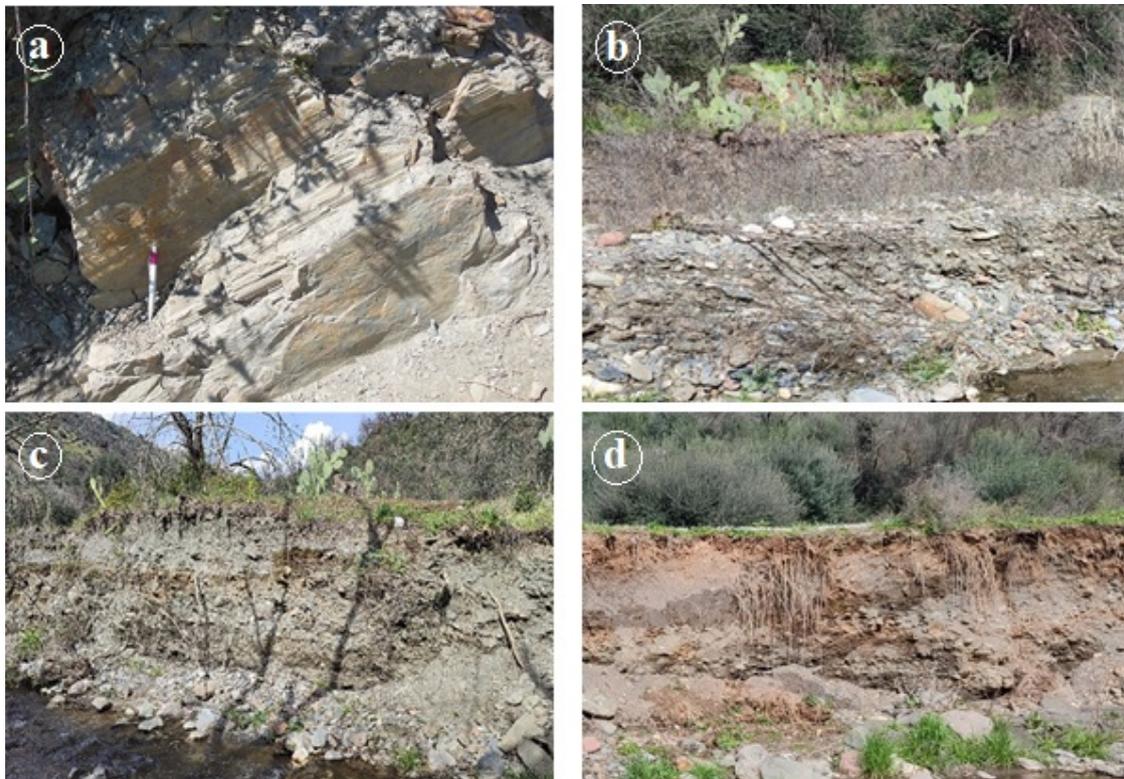
Figure 10. Neotectonics activities in part of Grande Kabylie. a. an undulating and striated fault mirror for oblique reverse fault with left-hand strike-slip; b. closely interlocking alluvial terraces in the rights bank of the Oued Djemaa; c. a fluvial overhang in Oued Djemaa; d. a reverse fault cutting across an alluvial terrace level.

6. CONCLUSIONS

The Alterites (alloterites and isalterites) and the relative tectonics activity index (Iat) obtained by estimating geomorphic indices are useful parameters for assessing active tectonics in anisotropic metamorphic terrain in Grande Kabylie and its relationship with landslides. The spatial variability of weathering profiles in relation to the relative tectonic activity index suggests that recent tectonics activity has influenced the dynamics of alteration processes, where the intensity of deformation controls the efficiency of supergene processes. It highlights the tectonics control of substratum fracturing, thickness, and distribution of alterites. These various observations support the hypothesis that the genesis of alterites is closely linked to neotectonics. The latter is related to the collision context resulting from the convergence of the African and Eurasian plates. This study demonstrates the usefulness of this integrated approach for assessing neotectonics activity, its relationship with the formation of alterites, and deformation and rupture of slopes in anisotropic metamorphic terrain. Our results will help decision- makers and academic researchers to better understand the assessment of active tectonics and landslides. They could thus enable the development of recommendations aimed at mitigating and/or stabilizing affected slopes, where human and economic issues are particularly sensitive to these phenomena.

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