

Assessment of Mass-Movement Instabilities along the Southwestern Escarpment of the Bamileke Plateau Using Geological, Geotechnical and Remote Sensing-Derived Lineaments

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Abstract

The southwestern escarpment of the Bamileke Plateau (SWEBP), located in the West Cameroon Highlands (WCH), is characterized by a high vulnerability to landslides. Numerous springs around vulnerable zones weaken materials and increase slope stress, leading to greater instability. The methodology combined lineament assessment from satellite imagery, an inventory of mass movement sites, and soil and rock sampling to assess the structural, geotechnical, and geological characteristics of SWEBP. The results show that the area is primarily composed of landslide-prone zones, accounting for 91.43% of landslides (32 landslides across 35 sites). Microscopic analysis shows that gneiss and granite are essentially rich in feldspars and biotite, which weather easily to form clay soils. The soil exhibits two horizons (HA and HBC), suggesting a high potential for displacement during a landslide. The soils of the SWEBP are classified into three categories: Andosols, Cambisols, and Ferrasols. The lineament map reveals zones of structural weakness that may promote mass movement. In total, 99 lineaments were identified, with a dominant NE-SW orientation and a secondary ENE-WSW trend. Geotechnical analyses of these soils show that they have an average specific weight (2.53 - 2.61 g/cm³), low dry densities (1.24 - 1.36 g/cm³), high wet densities (1.59 - 1.71 g/cm³), high porosity (47.37% - 51.21%), medium compactness (48% - 53%), high liquid limits (61.3% - 71.5%), low plastic limits (31.4% - 38.7%), high plasticity index (29.9% - 35%) and void ratios range from 0.90 to 1.05. Their water content is average to bad quality (24% -

31%), and they are mostly fine-grained (70.38% - 78.0%), and show low cohesion (0.22 - 0.45 bar) with high internal friction angles (22.3° - 26.1°). When associated with steep slopes (>25°), they are highly susceptible to mass movements. Identifying these risk zones is crucial, as mass movements reduce slope stability by weakening material cohesion and balance.

Keywords

Southwestern Escarpment of the Bamileke Plateau, Mass Movement, Geotechnics, West Cameroon Highlands, Remote Sensing Lineaments

1. Introduction

According to the International Federation of Red Cross and Red Crescent Societies (IFRC, 2020), the average annual number of disasters triggered by natural hazards has increased by approximately 25% since 1970. This trend is noticeable despite significant year-to-year variability. Mass movements are ranked seventh among major natural hazards based on the criterion of damage caused, after earthquakes, cyclones, and floods, among others (Dauphiné & Provitolo, 2013). The generic term “mass movements” refers to the detachment and displacement of soils and rock materials along slopes under the direct effect of gravitational forces (Rouiller et al., 1998). They exhibit a wide variety in their nature and behaviour (rockfalls, collapses, landslides, slides, creep, and subsidence) and in their size (Besson, 1996). The frequency of natural and man-made disasters in Cameroon has increased substantially over the past two decades (2000-2020). At least 5000 people lost their lives and more than 50000 head of livestock were decimated during the same period (Ghogomu et al., 2001). Over the past three decades, Cameroon has experienced catastrophic mass movements, including some thirty landslides that have resulted in the deaths of 128 people (Zogning et al., 2007). The situation regarding landslides and instabilities in Cameroon is becoming increasingly alarming, with so much damage recorded daily. Each year, cases of varying magnitude are recorded (Table 1). In the SWEBP, mass movements are recurrent during the rainy season, particularly in August and September, regularly resulting in significant material damage. These instabilities are exacerbated by the granitic and metamorphic nature of the formations, the presence of tectonic discontinuities, steep slopes, and high rainfall.

The intensification of urbanization and the effects of global climate change are now major factors exerting pressure on mountain areas. In the SWEBP, soil fertility combined with a shortage of habitable land encourages unplanned urbanization of the slopes. This haphazard land use increases the vulnerability of the population to geodynamic hazards, particularly mass movements. Due to this topography, the population is constantly exposed to natural hazards that affect the environment. Mass migrations are increasingly frequent today, affecting the environment over long periods and simultaneously hindering the country's econ-

omy. The WCH are characterized by a highly complex morphological landscape, consisting of volcanic mountains, high plateaus, and rift valleys (Aboubakar et al., 2013). The SWEBP, located within the WCH is characterized by marked human vulnerability. According to data from the 2013 Participatory Village-Level Diagnostic Survey (DPNV, 2013), the municipality of Bakou has an estimated population of approximately 5255 inhabitants. This population concentration is accompanied by environmental vulnerability, linked to the physical and socio-economic conditions of the area. Furthermore, these are areas of intense agricultural activity characterized by very fertile soils. With the population explosion in the SWEBP, residents tend to cultivate and settle in new areas subject to mass migration. The SWEBP is also characterized by the presence of numerous detachment niches and many steep areas. It is also crossed by the local road that connects Bafang to Nkondjock via Bakou, and Bafang to Baboutcha Fonga. Due to this topography, these populations are constantly exposed to natural hazards that affect the environment and hinder their agricultural and pastoral activities. The present study aims to evaluate slope instabilities along the SWEBP using an integrated approach combining lineament assessment, geological analyses and geotechnical tests in order to establish the relationship between the nature of the formations and their degree of fracturing, their physical and mechanical properties and susceptibility to mass movements, in order to contribute to a better understanding of destabilization processes and sustainable risk prevention in this particular geological context.

Table 1. Location of mass movements and resulting damage in Cameroon (Aboubakar et al., 2013 modified).

N°	Landslide locations	Damage	Year	References
1	Fossong-Wentcheng (Dschang)	6 deaths and destruction of plantations	August 1978	(Tchoua, 1984, 1989)
2	Pinyin	Destruction of plantations	1991	DPC, 2008
3	Santa	12 deaths	September 12, 1992	DPC, 2008
4	Bafaka	Destruction of plantations	1993	DPC, 2008
5	Nwa	Destruction of plantations	2000	DPC, 2008
6	Limbe	24 deaths	2001, 2009	Ayonghe et al., 2004
7	Bana	Destruction of plantations	September 10, 2002	Aboubakar et al., 2013
8	Maga	20 deaths	July 10, 2003	Kagou Dongmo, 2006
9	Bafou	2 deaths	2003	Zogning et al., 2007
10	Wabane	1 death	2003	DPC, 2008
11	Fondonera (SW Dschang)	Destruction of plantations	2008	Aboubakar et al., 2013
12	Abuh (Fundong NW Cameroun)	Destruction of plantations	September 27, 2007	DPC, 2008
13	Kekem	1 death	October 20, 2007	Aboubakar et al., 2013
14	Bamenda	Destruction of plantations and roads	2009	Aboubakar et al., 2013
15	Koutaba	2 deaths	October 23, 2011	Aboubakar et al., 2013

Continued

16	Bebong and Dabang	Significant material and environmental damage	August 4, 2017	Ndonbou, 2018
17	Njungo-Nguti, South west	Significant material and environmental damage	August 4, 2017	Nchadji, 2018
18	Essoh-Attah (South-West)	Loss of animals, destruction of houses and crops, and property damage	August 4, 2017	Djiague Tabagan, 2018
19	Fomopea	Three dead and extensive property damage	July 12-13, 2019	Zangméné, 2020
20	Ngouache (Bafoussam)	41 deaths	2019	Tangmouo Tsoata et al., 2020
21	Yaounde (Central Cameroon)	15 deaths	November 17, 2022	Nsounjoundi Mbouombou et al., 2025
22	Yaounde (Centre-Cameroun)	Destruction of homes and surrounding areas; 28 dead	October 8, 2023	Nsounjoundi Mbouombou et al., 2025
23	Dschang (Western Cameroon)	Approximately 12 deaths, destruction of machinery and crops, and the road linking Dschang to the Littoral region cut off	5 Novembre 2024	Bissaya et al., 2025

2. Geological and Geographical Context

The SWEBP is located between 5°06' and 4°55' North latitude and 10°04' and 10°13' East longitude. It has an area of approximately 197 km². The basement formations in the area consist of gneiss and granite partially covered by basalt and gabbro. The climate in the SWEBP is tropical humid with two seasons: a short dry season (December to February) and a long rainy season (March to November). The average annual temperature is around 25°C. Annual rainfall is abundant (134 mm ≤ average ≤ 429 mm) with peaks between August and September. The drainage network is dendritic to meandering, and the streams flow towards the north-east and northwest. According to studies conducted by Ngako et al., (2021) in Bafang, Bakou, Banka and in the district of Banwa, two main formations are observed: basement formations (cratonic and plutonic rocks (porphyroid type facies, anatectites), norite, biotite gneiss-embrechite, biotite gneiss and amphibolite) and overlying formations (basalts) located in specific locations.

3. Methods

3.1. Field Methods

The field campaigns conducted allowed for the sampling of materials. The first campaign consisted of identifying the different vulnerable areas. Several scars were identified in this area, but we focused on the most vulnerable zones (Figure 1). Approximately 35 vulnerable sites were identified (32 areas at risk of landslides with a percentage of 91.43% and 3 areas at risk of rockfalls compared to a percent-

age of 8.57%). These vulnerable sites are shown in **Figure 2**, which was extracted using Google Earth. Based on criteria such as the morphology of the different sites (steep and abrupt slopes) and the recurrence of minor landslides, six representative sites were selected to collect samples of disturbed and undisturbed soils for geotechnical analyses.



Figure 1. Overview of some vulnerable sites on the SWEBP. (a) Risk of rotational landslide; (b) rockfall risk2-Laboratory methods.

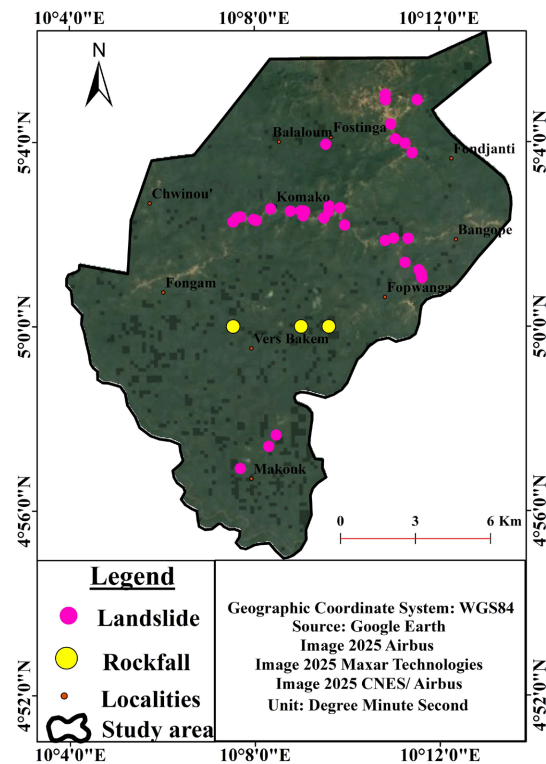


Figure 2. Mass movement density map of SWEBP (extracted from Google Earth).

For this study, 2 Rock samples were collected in December 2023 from the fresh and healthiest possible rock outcrops using a sledgehammer, with sampling points plotted on a topographic map using a GPS. The geographical coordinates of its sample are as follows: Gneiss (N5°02'34.39"; E10°09'50.9"; Altitude 1370 m); granite (N5°02'34.3"; E10°09'51"; Altitude 1253 m). These samples were taken from

the steep and unstable slopes of the most representative vulnerable sites.

Undisturbed soil samples were extracted on August 28, 29, 30 and 31, 2024 from the detachment niches at various vulnerable sites identified using a cylindrical corer and labelled in the order of collection. These samples were carefully preserved, waxed, and labelled in the order of collection for laboratory testing. Using 10 cm diameter and 25 cm high pipes, we collected undisturbed soil samples from each site (vulnerability zones). These samples were waxed using melted candle wax and labelled in the order of collection at the different sites for laboratory testing. During this extraction process, the collected soil was considered a disturbed sample. These collected disturbed soil samples were stored in plastic bags for laboratory testing. These samples represent the 35 vulnerable sites because they exhibit a high level of vulnerability.

The detachment niches allowed for the description of the soil profiles. The boundaries between the different horizons were determined by certain specific characteristics that appeared along the profile and soil levels. Colors were determined using the Munsell soil chart. Texture was determined in situ through manual tests, during which a moistened sample was rubbed between the fingers.

3.1.1. Lithology and Petrographic Analyses

Microscopic observation and petrographic description of the collected rocks were carried out using a polarizing microscope. It initially involved producing a rock sugar sample on which a glass slide was placed and then cut. These thin sections were prepared in the laboratory of the IGMR (Institute of Geological and Mining Research) in Nkolbisson, Yaounde, and were subsequently observed using a polarizing microscope at the laboratory of the Department of Earth Sciences of the University of Dschang. The mineralogical study was carried out using a petrographic microscope on thin sections, following two complementary observation modes: plane-polarized light (PPL) and cross-polarized light (XPL). These two techniques make it possible to characterize the optical and mineralogical properties of the studied samples. Observation in PPL is performed using a single polarizer placed beneath the thin section. While observation in XPL is carried out using two polarizers crossed at 90°; this mode allows the determination of the fine optical properties of minerals.

3.1.2. Geotechnical Parameters of the Soil

In this study, physical and mechanical soil identification tests were carried out on six samples (E₁, E₂, E₃, E₄, E₅, and E₆) taken from the different vulnerable sites (Fopwanga, Fondjanti, Balouk, Komako, Ndoko, and Koba). Laboratory experiments and calculation methods allowed us to determine the geotechnical parameters of the soil. Geotechnical analyses including physical identification tests (water content, specific gravity test, Atterberg limits, particle size analysis, and porosity) and mechanical tests (box shear test). These geotechnical parameters include, among others:

- **Particle size analysis:** This test allows for the dimensional distribution (parti-

cle size class) by weight of the grains in a soil material. The particle size data obtained will allow for the plotting of curves showing the variation of particle size classes as a function of the percentages of sieved material and the mesh size.

- **Atterberg limits:** These allow the determination of water content corresponding to the three states of materials: solid, plastic, and liquid. They are determined using the Casagrande apparatus. This involves the liquid limit (ω_L) and the plastic limit (ω_P), in addition to the plasticity index (P_I) and consistency index (C_I).

After the Plasticity Index (P_I) was obtained, values were compared to those in **Table 2** which gives the relationship between P_I and soils and helps to determine the level of vulnerability.

Table 2. Degree of soil plasticity as a function of the plasticity index.

Plasticity index (%)	Degree of plasticity
$0 < P_I < 5$	Non-plastic
$5 < P_I < 15$	Moderately plastic
$15 < P_I < 40$	Plastic
$P_I > 40$	Very plastic

- **Specific weight test or actual density:** This is the ratio of the weight of the solid particles of a material to the volume they occupy (it is the absolute density of an anhydrous material).

$$dr = M_s / V_s \quad (1)$$

The actual density is obtained using the following relationship:

$$dr = \frac{P_2 - P_1}{(P_4 - P_1) - (P_3 - P_2)} \quad (2)$$

- **Water content by weight:** This test determines the amount of water in a soil measured by steam drying. The water content is therefore obtained from these different masses.

$$\omega(\%) = \frac{M_2 - M_1}{M_3 - M_1} * 100 \quad (3)$$

After Water content (ω) was obtained, values were compared to those in **Table 3** which gives the relationship between ω and soils and helps to determine the level of vulnerability.

- **Dimensionless parameters:** These indicate the proportions of the different phases of a soil. We define:
 - **Porosity (n)** indicates the extent of voids, that is, whether the soil is loose or compact. It is defined as the ratio of void volume to total volume.

$$n = \frac{V_v}{V}; \quad (4)$$

- **The void ratio (e)**, whose meaning is analogous to that of porosity, is defined by the following relationship:

$$e = \frac{V_v}{V_s}; \quad (5)$$

- **The compactness denoted (C)**

$$C = \frac{\gamma_d}{\gamma_s}; \quad (6)$$

- **The box shear test:** Its purpose is to measure the failure characteristics of a saturated fine soil sample. It provides two mechanical parameters: cohesion and the angle of internal friction. The test measures the upper limits of shear stress in a soil sample and predicts slope failure due to shear stress.

Table 3. Classification of soils in terms of water content (Bonnard, 1993).

Soils	Water content
Exceptional	100 - 1000
Very bad	>45
Bad	45 - 30
Average quality	30 - 20
Good	20 - 12
Very good	<12

3.1.3. Physical Description of Soil Properties

The detachment niches allowed us to describe typical soil profiles. Two soil profiles were described. We determined the boundaries between the different horizons through specific characteristics that appeared along the profile and soil levels. Soils colours were determined using the Munsell soil chart. Texture was determined in situ using tactile tests, which involved rubbing a pre-moistened sample between the fingers to assess the relative proportions of the different grain sizes.

3.2. Extraction and Analysis of Lineaments from Satellite Images

The methodology consists of the extraction, processing and structural interpretation from the Landsat-8 OLI/TIRS satellite images of 27/02/2017 using an approach combining digital preprocessing, contrast enhancement and structural interpretation, thus allowing the extraction of lineaments in order to create a map of structural lineaments using ArcGIS software, which will thus allow the detection of geological structures (faults, ruptures, and tectonic directions) influencing the triggering of mass movements. The spectral bands used were selected for their ability to discriminate morphostructural contrasts: the visible (b2, b3, b4), near-infrared (b5), and mid-infrared (b6 and b7) bands. These combinations improve the distinction between structural discontinuities likely to correspond to lineaments.

ments. Directional statistical analysis of the lineaments obtained using Rock-Works software allowed us to construct a lineament direction rosette. Subsequently, the lineaments were correlated with the geology of the area to demonstrate the degree of fracturing of the local rocks.

3.2.1. Preprocessing Applied

Before lineament extraction, several preprocessing operations were performed to improve the visual and spectral quality of the images:

- **Radiometric and atmospheric correction:** The images were converted to surface reflectance to reduce the effects of atmospheric conditions, lighting, and atmospheric scattering.
- **Contrast enhancement:** Linear stretching of the histogram was applied to accentuate the contrast between homogeneous surfaces and linear structures.
- **Principal Component Analysis (PCA):** After contrast enhancement, Principal Component Analysis (PCA) was applied to the selected spectral bands to reduce information redundancy and improve the visualization of geological structures. PCA transforms the initial multispectral bands into a new set of uncorrelated images called principal components, ranked according to the variance explained. The first components generally contain most of the useful spectral information. In this study, the principal components from the Visible, NIR (Near Infrared), and SWIR (Short-wave Infrared) bands were examined visually and statistically. The components exhibiting the strongest structural contrasts (PC1, PC2, and PC3) were selected for structural analysis and lineament detection.
- **Directional spatial filtering:** Edge detection filters were applied to highlight topographic and textural breaks associated with fractures:
 - 7×7 Sobel filter: directional filters oriented along several azimuths (N–S, E–W, NE–SW, and NW–SE)
 - Laplacian filter (Prewitt and Yesou)

These processing techniques accentuate radiometric gradients corresponding to geological discontinuities.

3.2.2. Lineament Identification and Extraction

Lineaments were identified through visual interpretation. The criteria used for their identification were: spatial continuity; alignment of radiometric contrasts; the presence of topographic or morphological breaks; alignment of valleys, drains, or escarpments; and directional consistency with the regional structural context. The identified structures were vectorized in the ArcMap GIS environment to create a lineament database suitable for statistical and structural analyses.

3.2.3. Minimum Length Selected

To avoid including minor, insignificant artifacts and structures, a minimum length of 200 m was selected for the preservation of extracted lineaments. This threshold was chosen taking into account: the spatial resolution of the Landsat images (30 m); the desired level of generalization; and the need to prioritize major

structures with tectonic significance. Segments shorter than this were removed from the final dataset.

3.2.4. Elimination of Non-Geological Linear Structures

A validation phase was conducted to exclude linear structures of anthropogenic origin that could be confused with geological lineaments. The removed elements include, in particular: roads and tracks; agricultural or field boundaries; and urban infrastructure. This elimination was carried out by:

- Cross-referencing with topographic maps and land cover data;
- Comparison with road networks;
- Morphological and contextual analysis, as anthropogenic structures generally exhibit excessive straightness, regular geometry, and a spatial organization different from natural geological discontinuities.

4. Results

4.1. Lithology and Petrographic Results

Geologically, SWEBP is composed of gneisses, granites, conglomerates, lava flows and acidic lavas (phonolites, trachytes, rhyolites) (**Figure 3**) which are intensely fractured and occur as slab-like outcrops.

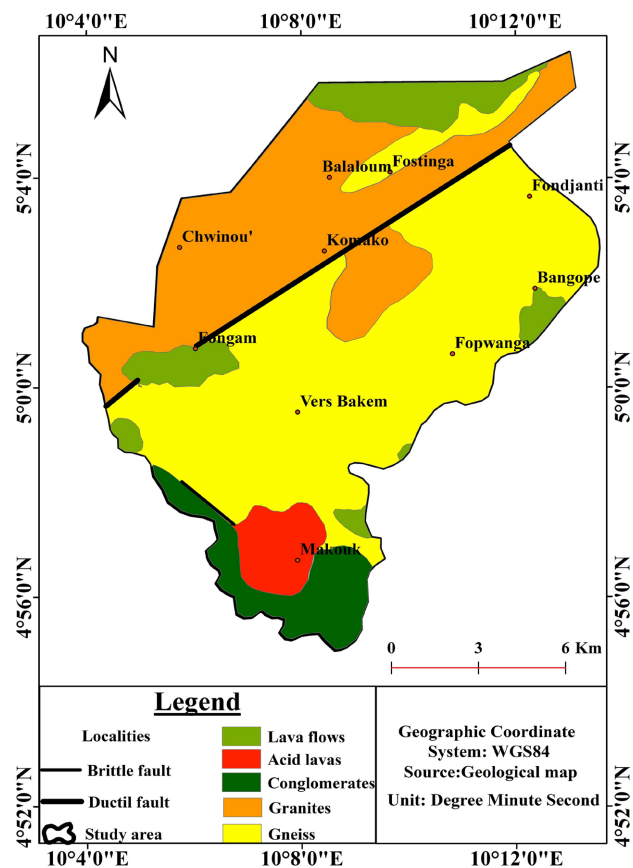


Figure 3. Geological map of the study area modified from the geological map of Delor et al. (2021).

4.1.1. Biotite Mylonitized Gneiss

It outcrops in slabs (**Figure 4(a)**). The rock is characterized by a coarse-grained structure (**Figure 4(b)**) composed mainly of alkali feldspar (orthoclase), quartz, and biotite; it has a heterogranular augen mylonitic texture (**Figure 4(c)**). Under the microscope, this rock shows more or less crushed minerals.

- **Alkali feldspars (35%):** These are primarily composed of orthoclase, characterized by Carlsbad twinning, and occur as xenomorphic crystals ranging in size from 0.1 mm to 1.2 mm. In PPL, they exhibit first-order grey polarization. They are highly altered. Some are peocilitic, containing rounded quartz crystals as inclusions.
- **Quartz (30%):** It occurs as subhedral and xenomorphic grains ranging in size from 0.1 mm to 0.8 mm (**Figure 4(f)**). In XPL, it displays low first-order interference colors and all grains exhibit undulating extinction. Some very small quartz crystals are found as inclusions within the alkali feldspars.
- **Biotite (20%):** Occurs as elongated brown flakes, ranging in size from 0.1 to 0.3 mm (**Figure 4(f)**). Under XPL, it displays moderate second-order interference colors and parallel extinction.
- **Plagioclase (15%):** Occurs as sub-hedral crystals with a lamellar shape. In XPL, it shows polysynthetic twinning (**Figure 4(e)**). These xenomorphic crystals range in size from 0.1 mm to 0.4 mm and also exhibit some edge reactions upon contact with quartz.

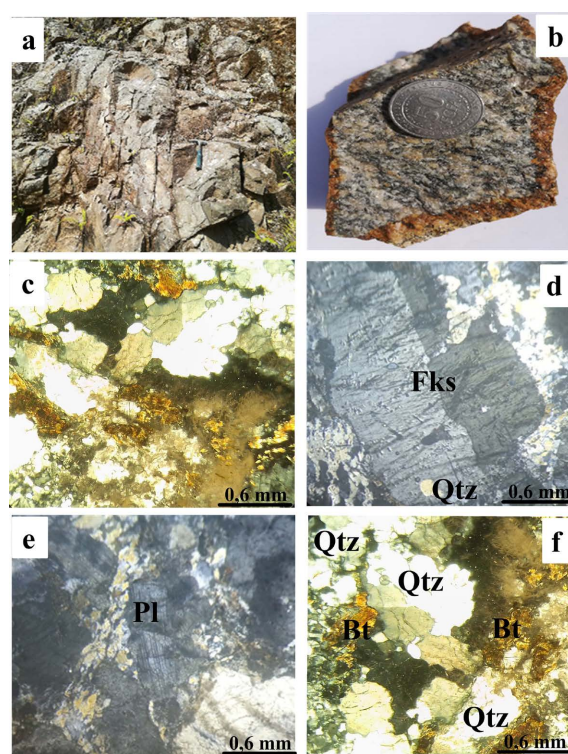


Figure 4. Photographs and photomicrographs of gneiss. (a) Gneiss outcrop; (b) Hand specimen of Gneiss; (c), (d) (e) and (f) photomicrographs of gneiss (Pl: plagioclase, Qtz: quartz, Bt: biotite, Fks: Alkali feldspars).

4.1.2. Granite

This rock is also fractured throughout. It outcrops in slabs (**Figure 5(a)**). It is fine-grained (**Figure 5(b)**). Under polarizing light, the rock displays biotite, alkali feldspars, quartz, opaque minerals, and plagioclase.

- **Biotite (35%):** Biotite occurs as elongated brown flakes, ranging from 0.1 to 1.5 mm. Some areas show larger biotite crystals (**Figure 5(d)**). The biotite crystals are intimately bound to the feldspars with straight contacts showing no edge reaction; some are found as inclusions (**Figure 5(e)**). In PPL, it exhibits pleochroism ranging from light brown to dark brown. Cleavage and a few rare quartz inclusions (**Figure 5(c)**) are present.
- **Alkali feldspars (30%):** Alkali feldspars are subhedral to xenomorphic with sizes varying between 0.1 mm and 0.6 mm (**Figure 5(e)**). They polarize in the first-order grays. The beginning of alteration of alkali feldspars is observed (**Figure 5(c)**).
- **Quartz (20%):** Quartz occurs as xenomorphic grains ranging in size from 0.1 mm to 0.6 mm (**Figure 5(f)**). The contact between quartz and other minerals is rectilinear, rarely curvilinear. All its grains exhibit undulating extinction. Some very small quartz crystals are found as inclusions within feldspars.
- **Plagioclase (15%):** Plagioclase occurs as polysynthetic twinned crystals. They are xenomorphic, ranging in size from 0.1 mm to 0.6 mm (**Figure 5(e)**), and are sometimes intercalated among untwinned crystals.

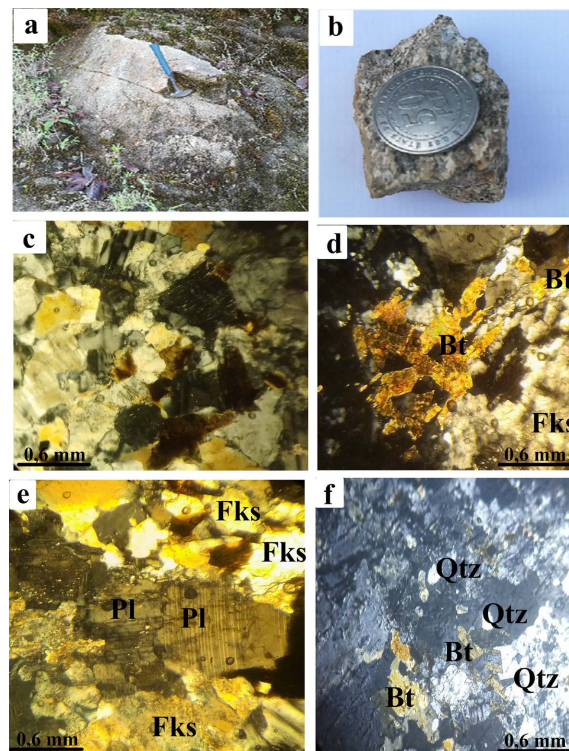


Figure 5. Photographs and photomicrographs of granite. (a) Granite outcrop; (b) Hand specimen of Granite; (c), (d), (e) and (f) photomicrographs (Pl: plagioclase, Qtz: quartz, Bt: biotite, Fks: Alkali feldspars).

The mineralogical assemblage of granite (Bt + Fks + Qtz + Pl) (**Table 4**) largely determines its geomechanical behaviour. That of biotite-bearing mylonitized gneiss (Fks + Qtz + Bt + Pl) exhibits anisotropy due to the presence of biotite. These mineralogical assemblages are crucial for slope stability because the progressive decomposition of feldspars and biotite into clay products leads to a decrease in intergranular cohesion, an increase in porosity and permeability, creating conditions favorable to slope destabilization and the initiation of mass movements.

Table 4. Paragenesis and mineralogical associations of the rocks in the study area.

Petrographic assemblages	Petrographic types	Textures	Mineralogical assemblages
Plutonic	Granites	Granular	Bt + Fks + Qtz + Pl
Metamorphic	Biotite mylonitized gneiss	mylonitic heterogranular	Fks + Qtz + Bt + Pl

4.2. Geotechnical Parameters of the Soil

Laboratory tests on samples of disturbed and undisturbed soils yielded the physical and mechanical parameters recorded in **Tables 5-7** respectively. These include, among others, specific weight or actual density, natural water content (ω_{Nat}), dry and wet density, particle size analysis (**Figure 6**), Atterberg limits (**Figure 7**), and straight-line shear in the box, in addition to other calculated physical parameters.

Table 5. Physical parameters of soils developed in the SWEBP.

Localities	Geographical coordinates			ω Nat%	Physical parameters						Atterberg limits			
	Lat	Long	Alt		γ_h (g/cm ³)	γ_d (g/cm ³)	γ_s (g/cm ³)	C	e	n (%)	ω_L	ω_P	P _I	C _I
Fopwangwa (E₁)	N5°01'03.1"	E10°11'37.2"	752 m	28.0	1.59	1.24	2.55	0.48	1.05	51.21	69.3	38.7	30.6	1.38
Fondjanti (E₂)	N5°04'23.2"	E10°11'03.1"	1323 m	26.0	1.64	1.30	2.58	0.50	0.98	49.50	65.2	33.2	32.0	1.20
Balouk (E₃)	N5°01'54.7"	E10°11'00.5"	984 m	28.0	1.71	1.34	2.61	0.51	0.95	48.72	61.3	31.4	29.9	1.11
Komako (E₄)	N5°02'16.3"	E10°07'31.9"	835 m	24.0	1.69	1.36	2.59	0.53	0.90	47.37	69.8	35.8	34.0	1.35
Ndoko (E₅)	N5°02'23.8"	E10°09'03.1"	1289 m	31.0	1.72	1.31	2.53	0.52	0.93	48.18	71.5	37.0	34.5	1.17
KOBA (E₆)	N5°02'11.8"	E10°09'57.1"	1274 m	27.0	1.66	1.30	2.55	0.51	0.95	48.78	68.5	35.4	33.0	1.25

- Porosity (n) is very high (47.37 - 51.21) (**Table 5**).
- The water content (ω) of the materials varies between 24% and 31%, which is very close to or even lower than the plastic limit ω_p (31.4% - 38.7%) (**Table 5**). According to **Bonnard's classification (1993)** (**Table 2**) the soils in the study area are of average to bad quality.
- Atterberg limits (**Table 5**): This refers to the liquid limit (ω_L) and the plasticity limit (ω_p), to which are added the indices of plasticity (P_i), liquidity (L_i), consistency (C_i), and handling (I_w).
- The plasticity indices are between 29.9% and 35% (**Table 3**) indicating very plastic soils that are likely to swell. According to the table of degrees of plasticity of a soil as a function of the plasticity index, (**Table 2**) we can say that the soils on the SWEBP are plastic soils.
- The most important particle size class in the SWEBP is that of clays and silts. Thus, these soils belong to the clay particle size class because the percentage of particles passing through the 0.08 μm sieve is greater than 35% (70% - 77%) (**Table 6**).
- The specific weight (γ_s) of the soils in the study area is average, being slightly less than 2.65 g/cm^3 , which is the average density of mineral solid particles (**Table 5**). These specific weight values are very close to each other in the six vulnerability zones.

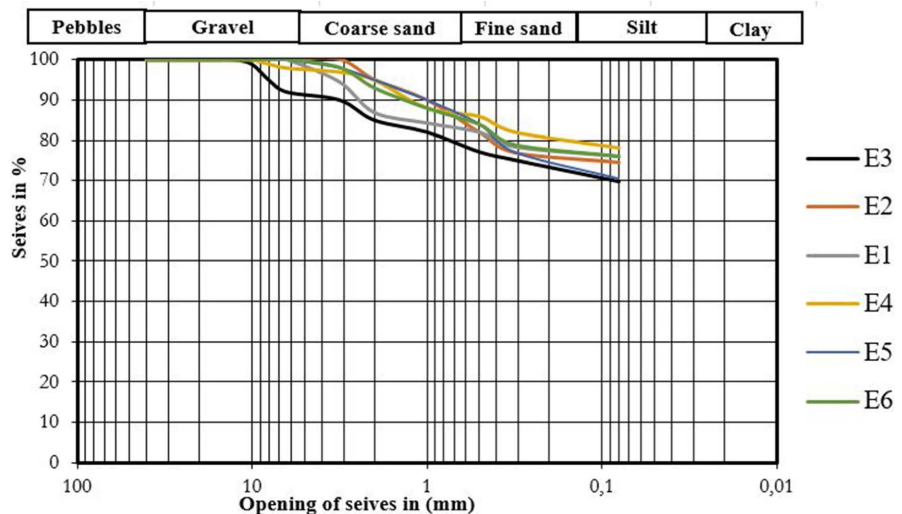
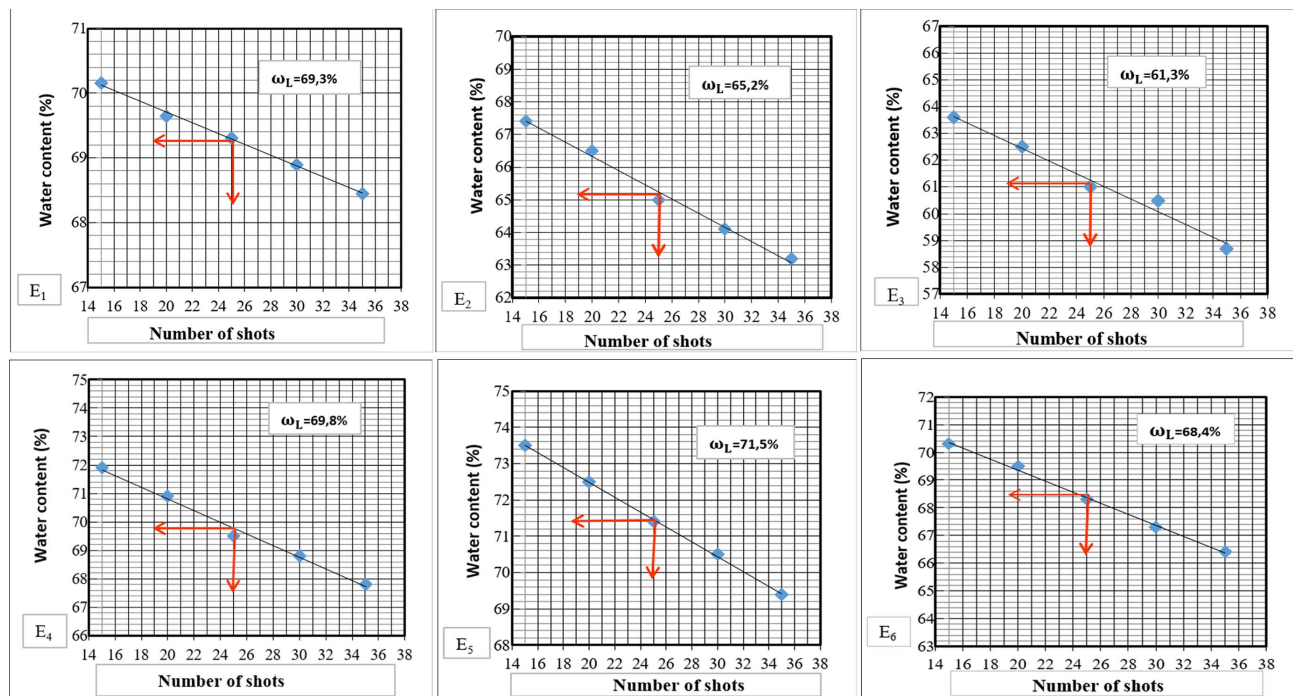


Figure 6. Particle size distribution curves of soils developed in the SWEBP.

- The soils of the SWEBP are subdivided into two classes (**Figure 6**): granular soils (gravel, coarse sand, fine sand) with a diameter greater than 0.02 mm and fine soils (clays and silts) with a diameter less than 0.02 mm. **Table 4** presents this distribution of the different granular classes.
- For shear, the samples underwent straight-line shear box tests or direct shear tests. The cohesion values C_u (bar) vary between 0.22 and 0.45 bars while the values of the angle of internal friction ϕ_u ($^\circ$) are high vary between (22 - 26) (**Table 7**).

Table 6. Grain size distribution of the different classes of soils developed in the SWEBP.

Materials	Brunish clay	Reddish clay	Reddish clay	Reddish clay	Reddish clay	Reddish clay
Samples	E ₁	E ₂	E ₃	E ₄	E ₅	E ₆
Pebbles	0	0	0	0	0	0
Gravel	13	5	15	5	5.2	6.8
Coarse sand	4.9	13	8	9.1	10.8	9.4
Fine sand	5.95	7.4	7.37	7.9	13.62	7.65
Clay and silt	76.15	74.6	69.63	78.0	70.38	76.15

**Figure 7.** Atterberg limits of the different soil samples developed in the SWEBP.**Table 7.** Mechanical parameters of soils developed in the SWEBP.

Samples	E ₁	E ₂	E ₃	E ₄	E ₅	E ₆
Cohesion Cu (bar)	0.26	0.24	0.45	0.22	0.42	0.29
Angle of internal friction ϕ_u (°)	26.1°	22.3°	25.7°	23.4°	23.9°	22.5°

4.3. Physical Properties of the Soil

1) Representative soil profile of Komako: It is located halfway up the slope, on a road cutting in the locality of Komako, and is situated at an altitude of 862 m. It has a height of 150 cm and consists of two soil horizons with irregular boundaries. From top to bottom we have:

- **Horizon A or organic horizon:** It is approximately 40 cm thick. This horizon is characterized by the presence of organic matter, a low degree of root pene-

tration, and very high levels of biological activity. This horizon has a clayey-sandy texture and a loose structure. It has a reddish-black colour (10YR4/4) which corresponds to dark yellow brown (**Figure 8(a)** and **Figure 8(b)**).

- **Horizon BC or weathering horizon:** Approximately 110 cm thick, it has a very low degree of root penetration and the presence of biological activity (porosity), including boulders. This horizon has a sandy-clayey texture and a compact structure. It has a brown colour (10YR4/3) which corresponds to brown (**Figure 8(a)** and **Figure 8(b)**).

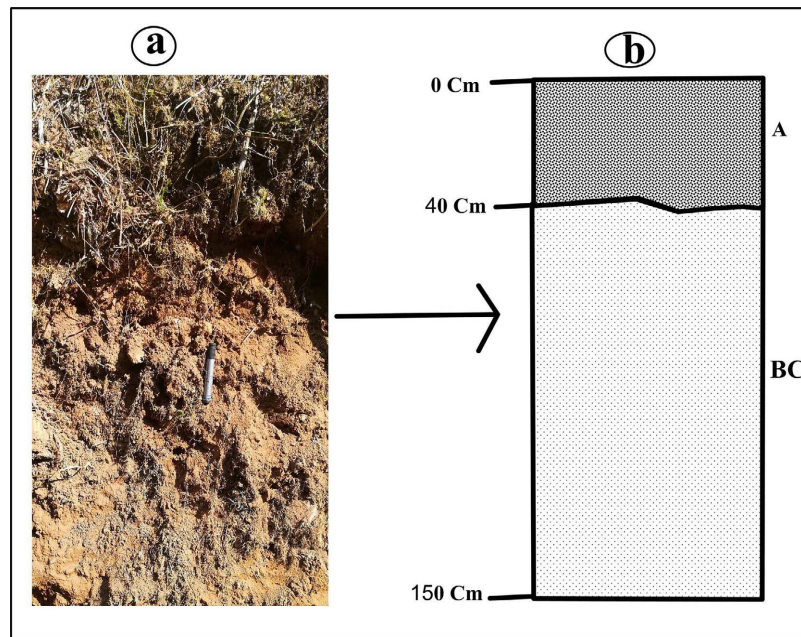


Figure 8. Soil profiles of Komako.

2) Representative Soil Profile of Koba: It is located mid-slope, on a road cutting in the Koba area. It has a height of 190 cm. This profile consists of two soil horizons with irregular boundaries. From top to bottom, we have:

- **Horizon A, or organic horizon:** It is approximately 30 cm thick. This horizon is characterized by the presence of organic matter (porosity), a low degree of root penetration, and very high levels of biological activity. This horizon has a clayey-sandy texture and a loose structure. It has a light brown color (2.5Y5/4), corresponding to light olive brown (**Figure 9(a)** and **Figure 9(b)**).
- **Horizon BC, or weathering horizon:** Approximately 160 cm thick, it exhibits a very low degree of root penetration and an absence of biological activity, with the presence of small rocks. This horizon has a sandy-clayey texture and a compact structure. It has a brown colour (2.5Y5/4), corresponding to light olive brown (**Figure 9(a)** and **Figure 9(b)**).

4.4. Structural Analysis

The lineament map (**Figure 10(a)**) obtained shows numerous fractures (99 linea-

ments), indicating that it represents areas of ground instability and therefore areas susceptible to mass movements. Statistical directional analysis of the lineaments obtained allowed the construction of a direction rosette (**Figure 10(b)**) of the lineaments in RockWorks to determine the dominant orientations representing highly fractured areas. The main direction of the fracture zones is shown in yellow, oriented NE-SW, and a secondary direction is shown in green, oriented ENE-WSW.

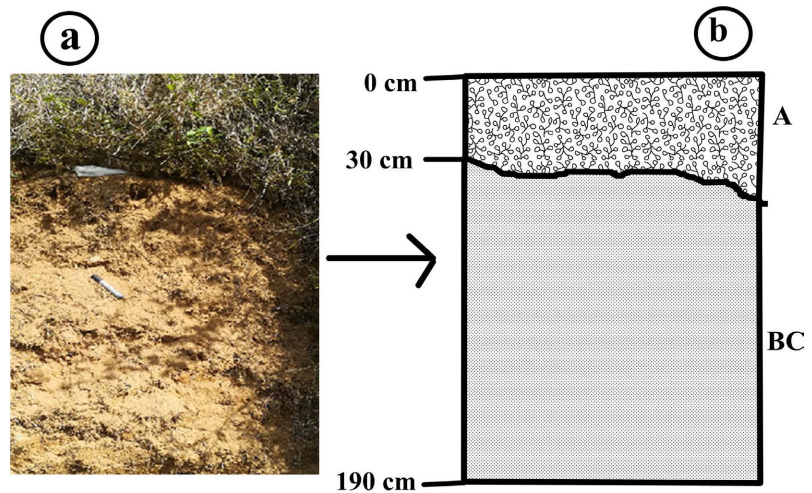


Figure 9. Soil profiles of Koba.

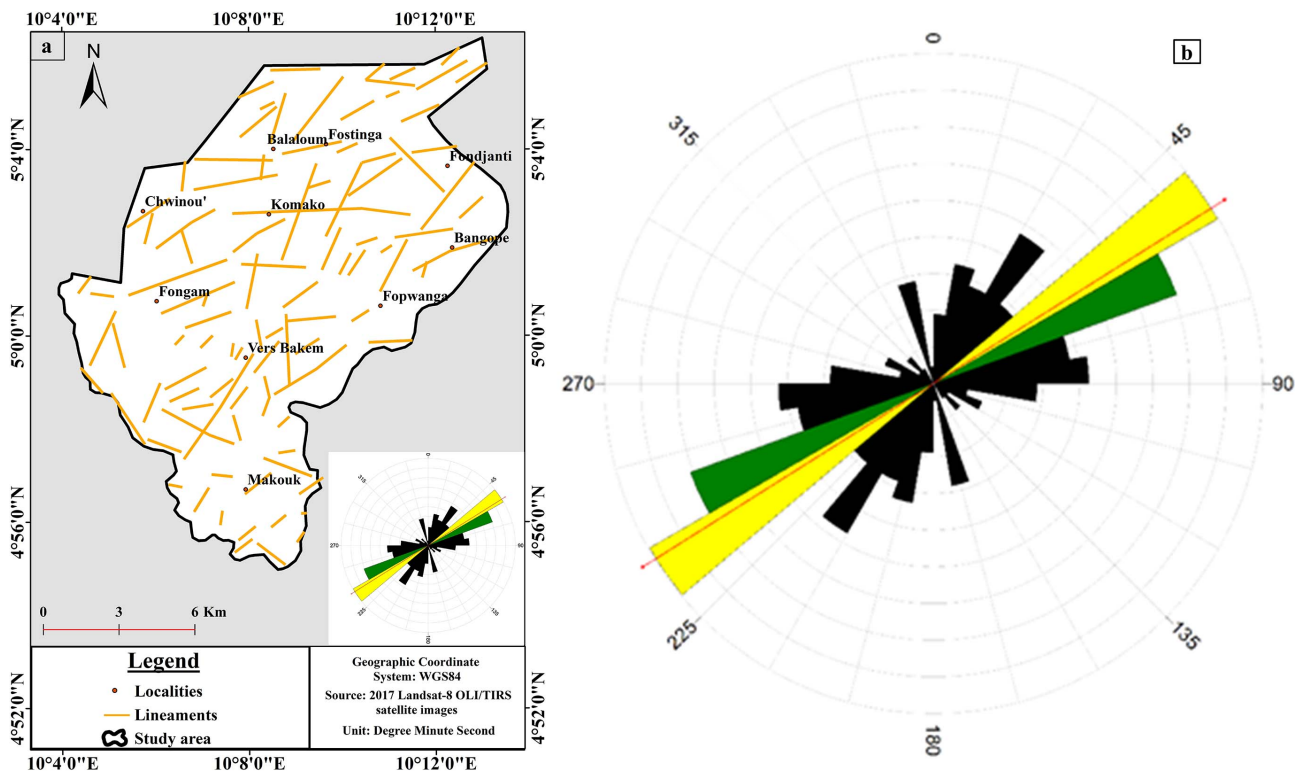


Figure 10. Lineaments and rose diagram of SWEPB. (a) Lineaments map, (b) Rose diagram.

The superposition of the lineaments with the geological map (Figure 11) of the area shows the high degree of fracturing of the SWEPB rocks.

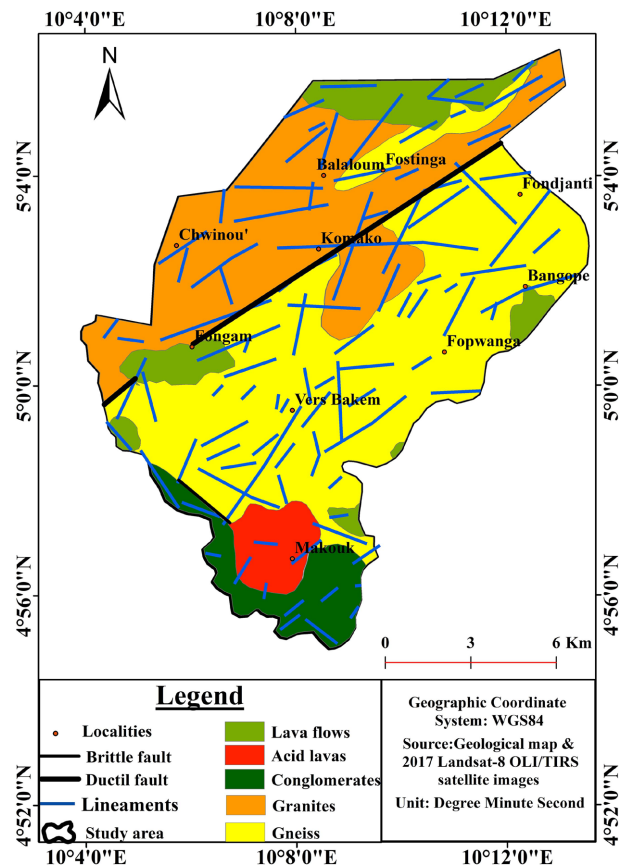


Figure 11. Lineament map associated with the geology of the SWEPB.

5. Discussion

Lithology is one of the factors that influences mass movements in the SWEPB. This has been demonstrated by [Ndonbou \(2024\)](#) and it is also one of the important factors causing instabilities in the Bamenda and Oku Mountains ([Djukem Wamba, 2021](#); [Guedjeo et al., 2017](#)). The instabilities recorded in the area are related to geological phenomena. The more oxides present in a rock, the higher the risk. The presence of oxides in rock and soils indicates advanced weathering, reducing cohesion and increasing porosity. These conditions promote water infiltration and create zones of weakness, thereby increasing the risk of landslides. The mineralogical composition of these rocks is dominated by feldspars (30%) and biotites (35%). The abundance of clays in the region is characterized by the weathering of alkali feldspars present in the rocks, which, by their very nature, promote slope instability. According to [Kebeba et al. \(2024\)](#), landslides are more likely to happen when rock formations are unstable and brittle. The local rocks (gneiss, granite) are rich in feldspars (alkali and plagioclase), biotite, and hornblende, which weather easily, giving rise to clay soils. This was demonstrated by [Abouba-](#)

kar et al. (2013) at Kekem, where the mineralogical composition of the rocks is dominated by feldspars, amphiboles, and biotites, minerals whose weathering ability index remains greater than or equal to 4 (Godard, 1962). The sandy nature of these soils is due to the weathering of granites. These rocks are highly fractured (Figure 4(a), Figure 5(a)), which promotes water infiltration and facilitates further weathering. The abundance of clay on the slope soils plays a significant role in slope instability. Previous studies show that the dominant petrographic types responsible for mass movements are mylonite, protomylonite, ultramylonite, granites, gneisses, basalts, and cataclastic rocks (Tcheumenak-Kouémo et al., 2014; Aboubakar et al., 2013). Their dense fractures make them easily crushed by water infiltrating to significant depths. These rocks exhibit a fractured and highly weathered appearance at the sites. Microscopic observations confirm this fractured appearance because the minerals present have significant fractures (Figures 4(c)-(e)). A high concentration of feldspar (Figure 4(d), Figure 5(a)) in the rock can be responsible for landslides because feldspars, through weathering, produce clayey materials (Anwi, 2011), and significant fracturing of the rocks, along with their extensive intrusions, facilitates the circulation of infiltrating water, thus rendering them unstable and predisposed to intense weathering (Djiague Tabagan, 2018).

In the occurrence of mass movements on the SWEPPB, the physical and mechanical properties of soils play a vital role. The characteristics and usability of these soils constitute factors that explain the occurrence of landslides in this area. Water content ranges from 24% to 31% due to the presence of fine particles. The soil retains water easily, which increases its weight and makes it more prone to sliding. These soils are primarily composed of fine particles (70.38% - 78.0%), exhibit low cohesion (0.22 bar - 0.45 bar) due to the nature of clay minerals, which have a high specific surface area and a high water-retention capacity, water accumulates within the soil mass. This water reduces the cohesive and adhesive forces between soil particles. Consequently, the shear strength of the slope may be reduced below the acting shear stress, potentially triggering a landslide. The internal friction angles are high ranging from 22.3° to 26.1° indicating relatively low shear resistance and suggesting that the slope is potentially unstable and susceptible to failure. These parameters in accordance with standards (Table 2, Table 3) combined with steep slopes (>25°), which expose the hillsides to potential instabilities show that the vulnerable sites of the SWEPPB have a high predisposition to mass movements. Average and poor water content values, low material cohesion and high friction angles have also been demonstrated by several authors (Aboubakar et al., 2013; Epada et al., 2012; Ndonbou, 2024). The Atterberg limits have the ability to affect the overall stability behaviour of the soils on the slopes (Ndonbou, 2024). The ω_L and ω_P values show that the soils are rich in clays, which become very unstable when they absorb water. These ω_L (61.3% - 71.5%), ω_P (31.4% - 38.7%) and P_L (29.9% - 34.5%) are in accordance with standards (Table 4) and are very close to those obtained by Ndonbou (2024) (Guedjeo et al., 2013). The po-

rosity (n) and void ratio (e) values are high due to the high specific surface area of clay minerals formed from the weathering of feldspars, which enables the soil to retain water easily; this is close to those reported by Poueme Djeuyap (2018), Zangméné (2020), Guedjeo et al. (2013), and Ndonbou (2024). Particle size analysis shows that the soils are fine-grained (70.38% - 78.0%) because the percentage of particles passing through the 0.08 μm sieve is greater than 35%, with fine sand, silt, and clay being the dominant particle sizes. These proportions are very close to those obtained by Guedjeo et al. (2013) on the Bamenda Escarpment (55% - 86%). Low cohesion and an abundance of fine particles reduce shear strength, while high porosity promotes water circulation and retention. These conditions lead to increased pore pressures and reduced effective stresses. Combined with steep slopes, they create an environment conducive to the initiation of mass movements.

Profiles were described at sites, located downslope, and these exhibit signs of instability as well as a high degree of vulnerability. The greater the degree of root penetration (the larger the roots), the more effectively they retain soil, and consequently, the lower the risk of landslides. The soil profiles of the SWEBP are primarily composed of two soil horizons with diffuse boundaries (HA and HBC). Soils profiles are characterized by: height (150 cm to 190 cm), small root size and clay-sandy nature; this indicates that a significant amount of soil could be displaced in the event of a future landslide. Water infiltration into these soils and their clay-sandy composition are sufficient factors to increase the risk of landslides. Three soil types are observed in the area: Andosols, Cambisols, and Ferrasols soils with sandy-clay and clay-sand textures. The work of Zangméné (2020) in the Yantou area shows soil types with the same characteristics (profiles with two soil horizons). This can be explained by the proximity of the parent rock on Mount Konfa.

Lineaments superimposed on the geology reveal the role of fractures and faults in slope predisposition to failure and in the path of landslides. Studies by Igwe (2018) demonstrated that lineaments influence landslides in a given dynamic environment. They create discontinuities in rock bodies that fragment the rock and accelerate weathering. The vulnerable slopes of the Nigerian-Cameroon highlands are also predisposed to failure by fractures and faults of various sizes (Igwe, 2018). Lineaments could pose significant threats in the future (Figure 9). The work carried out by Ngako et al. (2021) made it possible to identify 126 lineaments in the locality of Bakou with major NE-SW, ENE-WSW and E-W orientations.

These results show a strong correlation between mineralogical, structural, geotechnical properties and slope instability. The presence of numerous fractures increases the risk of mass movements. Clay-rich soils exhibit high sensitivity to water, which promotes swelling and loss of cohesion during the rainy season. Low friction angles, in turn, increase the probability of internal shear. Comparing these results in accordance with the standards with those of the authors cited above, we find that the results obtained along the SWEBP are, in one way or another, similar

to their findings. This allows us to confirm that the slopes along the vulnerable sites of the SWEBP have a high predisposition to mass movements, thus confirming the major role of weathering in instability.

6. Conclusion

This study investigates the instability within the SWEBP and identifies various contributing factors. The key findings are as follows:

From a geological perspective, the dominant rock types in the SWEBP are biotite mylonitized gneiss and granite, which are highly fractured and weathered, increasing their susceptibility to mass movements. Soil profiles in the locality are classified as AC type, indicating extensive soil weathering and material migration. Regarding the geotechnical properties of soil, the soil samples have high water retention capacity (26% - 31%) due to a large proportion of fine particles (69.63% - 78.0%). However, the soils exhibit very low cohesion (0.22 - 0.45 bar) while having a relatively high friction angle (22.3° - 26.1°). The SWEBP exhibits major NE-SW trending lineaments and minor ENE-WSW trending lineaments. These lineaments most likely correspond to fracture zones within the ESOPB rocks. They clearly control drainage and erosion of the region's hills. Regarding hydrological, rainwater infiltration increases pore pressure, reducing soil shear strength and cohesion, thus promoting instability. In the context of soil classification, the World Reference Base for Soil Resources (WRB) has made it possible to classify the soil of the SWEBP into three categories: Andosols, Cambisols, and Ferrasols. The clayey nature of the soils contributes to the likelihood of mass movements due to their poor cohesion and the increased susceptibility of the soil to water infiltration. The study shows that slope instabilities in the SWEBP are controlled by the interaction between weathering processes, unfavorable geotechnical properties and structural discontinuities which act as water circulation pathways and zones of mechanical weakness strongly influencing stability.

Concerning vulnerability and risk mitigation, SWEBP is highly prone to landslides and rockfalls, particularly due to its steep morphology. The presence of human settlements on slopes and near watercourses further increases the area's vulnerability. To mitigate these risks, it is recommended to construct buildings with deep foundations and retaining walls, especially in the Komako site, to better withstand the dangers associated with the steep slopes. As landslides often block roads during the rainy season (August and September), planting trees along roadsides is suggested. The deep roots of the trees would help stabilize the soil and absorb excess water. This knowledge about the risk will thus enable the population to be made aware and informed about these natural hazards as well as the emergency mechanisms to be put in place in the event of their occurrence.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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