

Geomatics Applied to Update the Geological Map of the Benoue Upstream Watershed (BUW)

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Abstract All hydrogeological exploration work is predicated upon a comprehensive geological assessment of the watershed. Consequently, an initiative was undertaken to update the geological map of the Benoue upstream watershed (BUW), with the objective of facilitating future characterization of the aquifers in this basin. To this end, Landsat OLI and SRTM satellite images of paths 155 and 055 were employed to discriminate the lithology through the use of multiple methods, including color composition, principal component analysis (PCA), band ratio, and MNF analysis. In Addition, borehole logs, when examined through their cross-sections, facilitated the establishment of these correlations. The results of the processing operations are then compared with the Ngaoundere East geological map (1961) in order to provide guidance with regard to lithological discrimination, and with the 2021 geological map. To corroborate the final rendering, a field campaign is conducted to geolocate the geological formations at critical points and superimpose them on indices obtained through processing, thus facilitating the final perfection of the map. In total, six geological facies have been mapped at a scale of 1:50,000, forming the basis for future work.

Keywords: Color composition, band ratio, PCA, MNF, SRTM, Lineaments

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1. Introduction

A historical overview of the geological work conducted in Cameroon can be summarized as follows: Prior to independence, extensive geological mapping was conducted by BUMIFOM, now known as BRGM and numerous university researchers, resulting in the publication of several 1:500,000 scale geological maps [1]. Additionally, preliminary work was conducted during the German colonial period until the eve of World War I, resulting in the publication of geological sketches at 1:500,000 and the discovery of certain mineral occurrences and deposits, including rutile in 1908. In 1979, the 1:1,000,000 geological map was published, providing a synthesis of the sixteen 1:500,000 reconnaissance sections, accompanied by an explanatory note in 1986. Furthermore, the map of 2001 by [2] and the 1:1,000,000 map of 2021 by the Ministry of Mines, Industry and Technological Development have been published. Over time, these diverse works have highlighted groups of

geological formations and their characterization according to geomorphological domains. The basement of the Adamaoua plateau is composed of metamorphic rocks of Paleoproterozoic age (2.1 billion years) [3,4,5], which have been intensely remobilized by the Pan-African orogeny [2,6].

The area is intruded by numerous granitoid intrusions, with an age range of 615 ± 27 to 575 million years [5,7]. Additionally, post-Pan-African dolerite dykes are present [8]. Recent research in the Meiganga region has been conducted by [9] on the petrography and structure of the Goumbela locality and by [10] on the geothermal potential of the Kaladi locality. [11,12] conducted a study of the syntectonic plutons of the Tibati region. These include diorites, tonalites, granodiorites, and granites that were emplaced along the Central Cameroon Shear. In the Meiganga pyroxene-amphibole gneisses, [5] demonstrate the presence of geochemical and 207Pb/206Pb age fingerprints that can be attributed to the Archean legacy. The structural, petrographic, and geochemical data on the Ngaoundere granites led [7] to the conclusion that these rocks were emplaced in a syn- or post-collisional

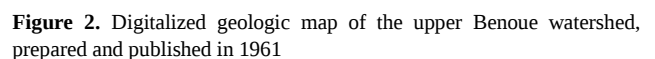
- Identify the principal petrographic units through image processing;
- Compare the processing results with previous research and field observations;
- Produce an updated geological map of the upstream Benoue watershed.

2.1. Geographical and Climatic Characterisation

From a geomorphological perspective, the basin's relief can be described as a peneplain, situated within the northern edges of the Ngaoundere escarpment. The landscape is punctuated by the occasional butte and rocky hill, which have been eroded by wind and water. The slope of the terrain ranges from 0 to 10%. The region's peak altitudes range from 1,150 to 1,400 meters, while its average altitudes are between 750 and 1,100 meters. The region is marked by the presence of small relief domes. The valleys, which are drained during periods of flooding are located in low land areas (altitude between 450 and 700 meters).



From a geological and structural standpoint, the upstream Benoue watershed is situated within the central Adamaoua-Yade zone. The area is bounded to the north by the Tcholiire-Banyo shear zone and to the south by the Sanaga fault [5,20]. The work of [7] on the Ngaoundere granitoids, in conjunction with that of [21], as well as an examination of historical cartographic materials, specifically the geological map of Ngaoundere from 1961, enabled the identification of eight distinct geologic facies: basalts, granites, gneisses, and differentiated formations (embrechists, anatexites).



3.1. Materials and Data

To accomplish this task, a variety of tools and data sets were employed. These included the Landsat OLI image of January 28, 2021, captured from paths and rows 185 and 055; a topographic map; an older geological map; and SRTM images of the aforementioned paths and rows. The Global Positioning System (GPS) receiver was employed to determine the geographic coordinates of the hydraulic

structures. The utilisation of software such as Word, Excel, Erdas and ArcGIS enabled the processing, digitisation and production of cartographic information.

The rationale decision behind the utilization of Landsat 8 is due to its multispectral radiometer, which encompasses spectral bands spanning from the visible to the mid-infrared, in contrast to the outcomes observed in previous Landsat series. Furthermore, two additional bands have been incorporated, providing atmospheric correction (the blue band at 440 m) and cloud detection (the 1380 m band), in addition to a quality assessment (QA) band where each pixel contains a decimal value. Upon transformation of this value into a 16-bit binary number, the ability to detect specific details of the Earth's surface, subsoil, and atmosphere is enabled.

3.2. Methods

3.2.1. Field Work

The field data collection stage entails the geo-localisation of geological formations and the measurement of attitudes, with the objective of constructing a geological database that will be employed to validate the geological model obtained subsequent to processing.

3.2.2. Image Processing

The image pre-processing, which was conducted as part of the work presented in reference [20], served to establish the link between watershed structures and the production of hydraulic structures. The geological bodies were distinguished by identifying the optimal composites through the IOF calculation (Table 2, Table 4, Table 7, and Table 9), which was based on the correlation matrix (Table 1, Table 3, Table 6, and Table 8). The mapping of linear structures was achieved through the utilisation of directional filtering with 7x7 convolution matrices.

3.2.2.1. Color Composition (CC)

Remote sensing images are in raster mode and are expressed in pixels. Each pixel contains a radiometric value, which provides information regarding the brightness and color of the feature in question. A raster file is composed of one or more-color channels. Each image is associated with a particular spectral band, reflecting the band in which it was acquired. The variety of Landsat channels provides numerous possibilities for band combinations. It is not uncommon for the information contained in the bands to be repetitive. To address this repetitiveness and identify the most salient RGB compositions, a statistical analysis of the bands within the metafile is conducted. The correlation matrix (see Table 1) was employed to calculate the correlation coefficient and associated deviations. The combination with the highest OIF is likely to provide the most lithological information, as it employs data with the fewest redundancies. Furthermore, the Index Factor Optimum is calculated.

The formula is as follows: $OIF = \frac{\sum_{k=1}^3 S_k}{\sum_{j=1}^3 |r_{kj}|} \quad (1) \quad \sum S_k$

The sum of the standard deviations of the combinations of

the three bands (k1, k2, k3) is presented herewith. The sum of the absolute values of the correlation coefficient.

Table 1. presents a correlation matrix for color composition

Spectral bands	B2	B3	B4	B5	B6	B7
B2	1.00	0.92	0.41	0.81	0.71	0.87
B3	0.92	1.00	0.66	0.77	0.64	0.76
B4	0.41	0.66	1.00	0.48	0.43	0.36
B5	0.81	0.77	0.48	1.00	0.96	0.93
B6	0.71	0.64	0.43	0.96	1.00	0.92
B7	0.87	0.76	0.36	0.93	0.92	1.00

The correlation matrix facilitated the calculation of the IOF and the identification of the optimal combination. The result of this calculation (see Table 2) demonstrates that the 2-4-6 combination exhibits the optimal IOF.

Table 2. The outcome of the OIF calculation for color composition

N°	Bands	Bands	Bands	OIF
1	B2	B4	B6	114.24
2	B2	B4	B7	106.70
3	B4	B6	B7	103.93
4	B2	B4	B5	102.84
5	B3	B4	B6	101.46
6	B4	B5	B7	99.21

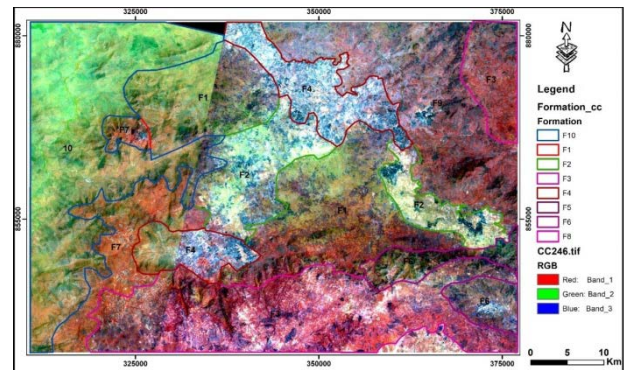


Figure 3. Color composition bands (2-4-6)

3.2.2.2. Principal Component Analysis (PCA)

Principal component analysis (PCA) is a mathematical transformation that involves calculating the eigenvalues and eigenvectors of the variance-covariance matrix derived from a series of images. This is followed by the calculation of the principal components of the multispectral band count [22]. The bands were correlated (Table 3) in order to calculate the IOF (Table 4). The results demonstrate that the optimal combination is 1-2-6.

Table 3. Band correlation matrix for principal component analysis

PC	PC1	PC2	PC3	PC4	PC5	PC6	PC7
PC1	1.00	0.15	0.22	0.29	0.27	-0.07	1.00
PC2	0.15	1.00	-0.10	-0.08	-0.13	0.05	0.15
PC3	0.22	-0.10	1.00	-0.17	-0.22	0.04	0.22
PC4	0.29	-0.08	-0.17	1.00	-0.11	-0.04	0.29
PC5	0.27	-0.13	-0.22	-0.11	1.00	-0.02	0.27
PC6	-0.07	0.05	0.04	-0.04	-0.02	1.00	-0.07
PC7	1.00	0.15	0.22	0.29	0.27	-0.07	1.00

Table 4. Result of IOF calculation for Principal Component Analysis

N°	Principal Component	Principal Component	Principal Component	OIF
1	PC1	PC2	PC6	1307.67
2	PC1	PC5	PC6	971.69
3	PC1	PC4	PC6	923.08
4	PC1	PC3	PC6	867.65
5	PC1	PC3	PC5	640.17
6	PC1	PC2	PC3	618.21

3.2.2.3. Band Ratio (BR)

Band ratio is a technique for dividing the digital counts of one band by another, thereby facilitating the discrimination of the desired feature according to its reflectance [23]. It can also elucidate information obscured by topography. In this study, 12-band ratios were employed for the purpose of identifying lithological units and mineral bodies (see Table 5). The radiometric behavior of a given body is recorded as a function of the wavelengths that are crossed. The selection of bands is contingent upon the specific absorbance and reflectance characteristics of the element in question.

Table 5. Different reports carried out

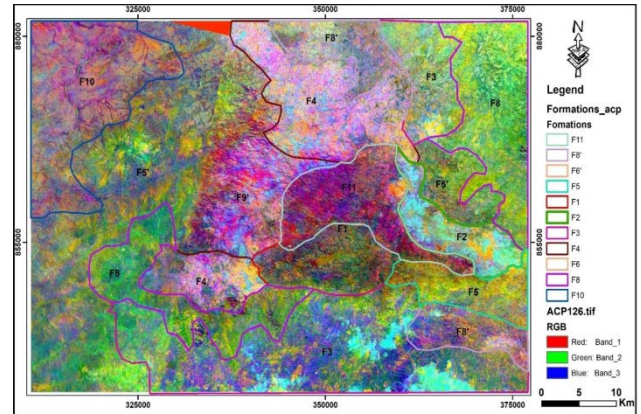
N°	Report	Code	N°	Report	Code
1	6/7	(1)	7	6/2	(7)
2	5/6	(2)	8	6/5	(8)
3	2/4	(3)	9	5/3	(9)
4	6/4	(4)	10	4/2	(10)
5	4/2	(5)	11	2/3	(11)
6	7/6	(6)	12	6/5	(12)

Table 6. Presents the correlation matrix for band ratios

Codes	(1)	(10)	(11)	(12)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1)	1.00	0.25	-0.10	-0.19	0.21	-0.24	0.14	0.25	-0.97	0.46	-0.19	0.54
(10)	0.25	1.00	-0.68	0.56	-0.54	-0.97	-0.64	1.00	-0.22	0.71	0.56	0.12
(11)	-0.10	-0.68	1.00	0.02	0.02	0.72	0.84	-0.68	0.12	-0.15	0.02	0.43
(12)	-0.19	0.56	0.02	1.00	-0.96	-0.52	-0.09	0.56	0.22	0.63	1.00	0.26
(2)	0.21	-0.54	0.02	-0.96	1.00	0.55	0.13	-0.54	-0.18	-0.61	-0.96	-0.24
(3)	-0.24	-0.97	0.72	-0.52	0.55	1.00	0.65	-0.97	0.26	-0.70	-0.52	-0.11
(4)	0.14	-0.64	0.84	-0.09	0.13	0.65	1.00	-0.64	-0.13	0.06	-0.09	0.63
(5)	0.25	1.00	-0.68	0.56	-0.54	-0.97	-0.64	1.00	-0.22	0.71	0.56	0.12
(6)	-0.97	-0.22	0.12	0.22	-0.18	0.26	-0.13	-0.22	1.00	-0.43	0.22	-0.53
(7)	0.46	0.71	-0.15	0.63	-0.61	-0.70	0.06	0.71	-0.43	1.00	0.63	0.74
(8)	-0.19	0.56	0.02	1.00	-0.96	-0.52	-0.09	0.56	0.22	0.63	1.00	0.26
(9)	0.54	0.12	0.43	0.26	-0.24	-0.11	0.63	0.12	-0.53	0.74	0.26	1.00

Table 7. Presents the OIF results calculated on the basis of the band reports

N°	Codes	Codes	Codes	OIF
1	(3)	(4)	(7)	17013.65
2	(11)	(6)	(9)	6788.27
3	(12)	(3)	(4)	4023.46
4	(3)	(4)	(8)	4023.46
5	(10)	(6)	(7)	2956.50
6	(5)	(6)	(7)	2956.50

**Figure 4. Band 1-2-6 in Principal Component Analysis**

The aforementioned products were combined in order to produce the most optimal composites, as determined by the IOF calculation utilizing the correlation matrix (Table 6).

The outcome of the IOF calculation permitted the consolidation of ratios (3), (4), and (7), which yielded the optimal result (see Table 7).

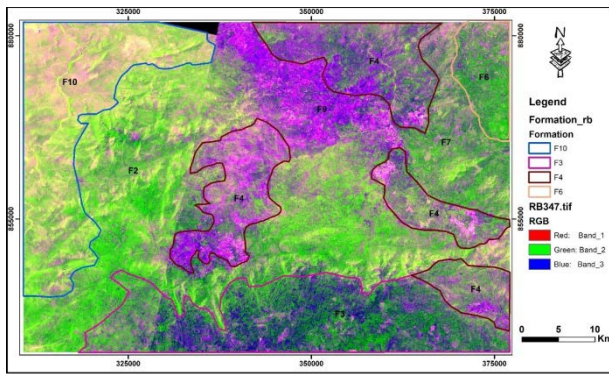


Figure 5. 3-4-7 band ratio combination

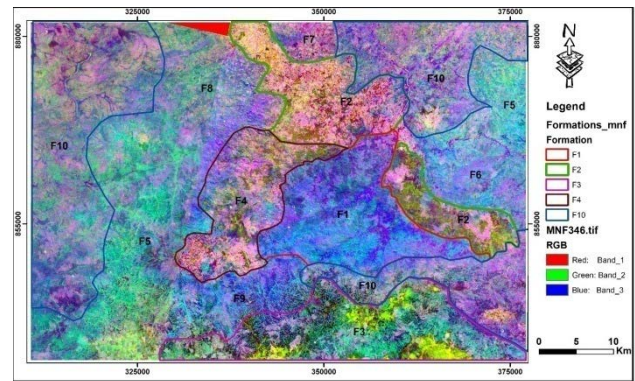


Figure 6. MNF bands (3-4-6)

3.2.2.4. Minimum Noise Fraction (MNF)

The Minimum Noise Fraction (MNF) analysis is employed to discern variations between bands in an image and to identify anomalous spectral features. This analysis is of significant importance in the field of mineral resource prospecting [24]. Additionally, MNF transformation is employed to ascertain the intrinsic dimensionality of image data, thereby enabling the isolation of noise and the reduction of computational demands for subsequent processing [25]. It is a method that is analogous to or similar to principal component analysis (PCA), which involves the preparation of the principal components in accordance with the information they contain. As stated by [26], the initial MNF bands encompass signals, while the subsequent bands comprise noise. A MNF transformation was applied to the near-infrared (PIR) and mid-infrared (MIR) bands, and the resulting data were correlated (see Table 6). To generate the color compositions, the OIF was calculated. The combination of bands with the optimal OIF was selected for this phase (Table 7).

Table 8. MNF band correlation matrix

MNF	MNF1	MNF2	MNF3	MNF4	MNF5	MNF6	MNF7
MNF1	1.00	-0.54	0.14	-0.22	0.14	0.07	1.00
MNF2	-0.54	1.00	0.06	-0.11	0.05	0.06	-0.54
MNF3	0.14	0.06	1.00	0.02	0.05	0.05	0.14
MNF4	-0.22	-0.11	0.02	1.00	0.06	-0.00	-0.22
MNF5	0.14	0.05	0.05	0.06	1.00	0.07	0.14
MNF6	0.07	0.06	0.05	-0.00	0.07	1.00	0.07
MNF7	1.00	-0.54	0.14	-0.22	0.14	0.07	1.00

Table 9. Outcome OIF calculation

N°	Bands	Bands	Bands	OIF
1	MNF3	MNF4	MNF6	2335.45
2	MNF4	MNF5	MNF6	1262.32
3	MNF3	MNF4	MNF5	1256.46
4	MNF2	MNF3	MNF5	1098.31
5	MNF2	MNF3	MNF6	981.07
6	MNF2	MNF5	MNF6	951.58

The results indicate that the most significant combination is MNF3-MNF4-MNF6.

3.2.2.5. Lineament Mapping

The application of remote sensing technology and GIS has been demonstrated to be an effective approach for the mapping of geological lineaments [21,27,28,29] [30,31,32,33,34]. To achieve this mapping, a number of operations are required. The work of [20,34,35] presents these different operations in detail. For this case study, the steps involved in producing the BUW fracturing map are clearly defined in the work of [21], which should be consulted as a reference. The digitization of linear structures is achieved through the use of 7 x 7 convolution matrices, as demonstrated in [21,47,48] (Table 10). The various stages that facilitated the mapping of the BUW structure are illustrated in Figure 8 below.

Table 10. 7x7 convolution matrix [21,47]

Sobel N-S						
0	1	1	1	1	1	2
-1	0	2	2	2	3	1
-1	-2	0	3	4	2	1
-1	-2	-3	0	3	2	1
-1	-2	-4	-3	0	2	1
-1	-3	-2	-2	-2	0	1
-2	-1	-1	-1	-1	-1	1
Sobel NO-SE						
-1	-1	-1	0	1	1	1
-1	-1	-2	0	2	1	1
-1	-2	-3	0	3	2	1
-2	-3	-4	0	4	3	2
-1	-2	-3	0	3	2	1
-1	-1	-2	0	2	1	1
-1	-1	-1	0	1	1	1
Prewitt						
1	1	1	1	1	1	1
1	1	1	1	1	1	1
1	1	1	1	1	1	1
-1	-2	-3	-7	1	1	1
-1	-2	-3	-3	1	1	1
-1	-2	-2	-2	1	1	1
-1	-1	-1	-1	1	1	1
Sobel E-O						
1	2	1	1	1	1	0
1	3	2	2	2	0	1
1	2	4	3	0	-2	-1
1	2	3	0	-3	-2	-1
1	2	0	-3	-4	-2	-1
1	0	-2	-2	-2	-3	-1
1	-1	-1	-1	-1	-1	-2
Sobel NE-SO						
1	1	1	2	1	1	1
1	1	2	3	2	1	1
1	2	3	4	3	2	1
0	0	0	0	0	0	0
-1	-2	-3	-4	-3	-2	-1
-1	-1	-2	-3	-2	-1	-1
-1	-1	-1	-2	-1	-1	-1
Yesou						
1	1	1	1	1	1	1
1	1	1	1	1	1	1
1	1	1	1	1	1	1
0	0	0	0	0	0	-1
-1	-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1	-1
-1	-1	-1	-1	-1	-1	-1

3.2.3. Outcomes Validation

This stage validates the results obtained from image

processing by analysing and superimpose on field data. It consists in building a geological database from field observations in order to refine the final geological map. The work of [21] clearly defines the methods used to validate lineament mapping as a fracture map of the BVAB. The geological mapping was highlighted using geo-localized field observations (lithological nature, pedological contrast, etc.) combined with the image-processing synthesis map and correlated with old maps.

geo-localized field observations (lithological nature, pedological contrast, etc.) combined with the image-processing synthesis map and correlated with old maps.

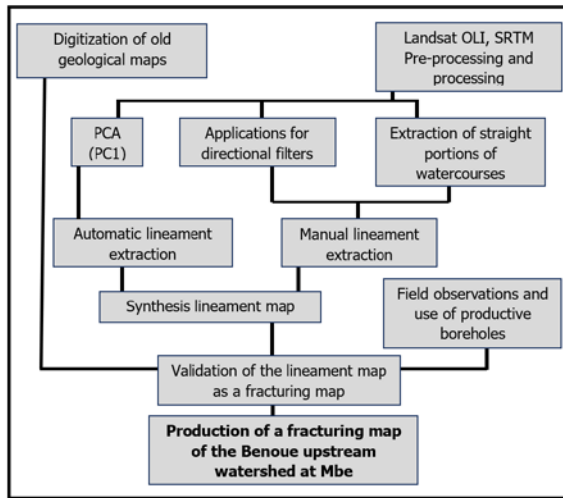


Figure 7. Illustrates the design diagram for the fracturing map of the upstream Benoue watershed



Figure 8. Operational phase of geological data collection

4. Results

4.1. Lithological Discrimination

Figure 11 illustrates the outcomes of the processing and validation procedures. The results demonstrate the presence of six distinct geological facies, including gneiss (orthogneiss and migmatitic gneiss), granite (monzogranite and leucocrate granite), and schist, in addition to basaltic flows. The BUW is predominantly composed of gneiss.

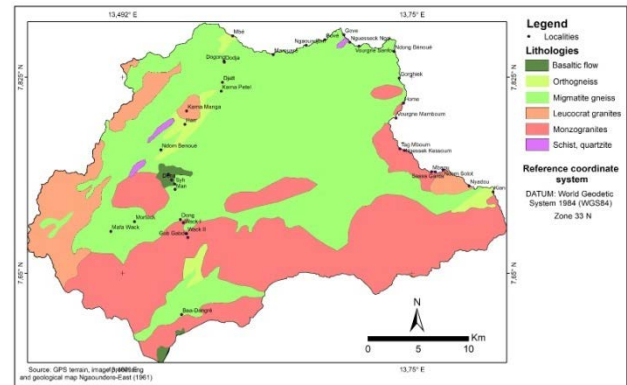


Figure 9. Lithology of the upstream Benoue watershed

4.2. Lineament Mapping

Following enhancement and the application of filters (Sobel, Prewitt, and Yesou), a total of 5,343 fractures of varying directions and lengths were mapped [21]. The work of these authors has enabled the classification of these structures by direction using the directional rosette. The major directions are observed in the northeast quadrant, while the minor directions are observed in the northwest quadrant.

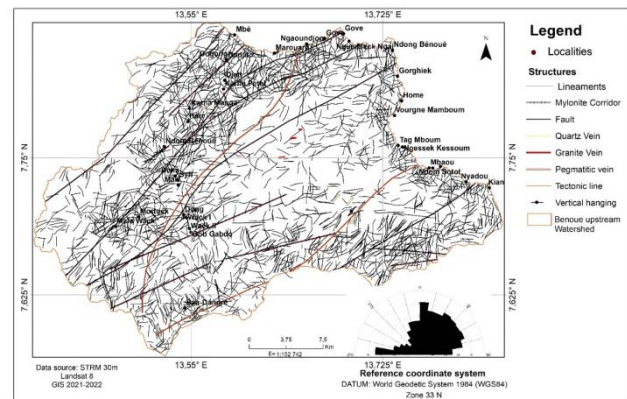


Figure 10. Fracturing of the Benoue upstream watershed at Mbe [21]

5. Discussions

The updating of the BUW geological map was made possible by the application of appropriate processing methods (CC, ACP, RP, MNF, and filtering), in conjunction with field campaigns and correlation with previous research. The details observed on the map provide evidence of significant geological phenomena,

including faults, fractures, and evidence of volcanism and geological contacts that are likely to influence the infiltration and flow of groundwater towards the BUW aquifers. However, linear extraction methods that employ directional filtering and the extraction of rectilinear portions of watercourses have been demonstrated to be both time- and cost-efficient. The quality of the information obtained is contingent upon the quality of the processing applied to the image utilized. As stated by [37], the object-oriented analysis of SRTM radar interferometry images allows for the automatic and efficient extraction of reliable information, thereby providing a foundation for sound management decisions in hydrogeological studies.

An analysis of the lineaments and directional rosettes indicates the presence of significant north-south deformation, with a predominant direction of N005°E. Furthermore, the N065° and N075° directions are also of significance, exhibiting a close alignment with the overall deformation orientation of the N70°E Adamaoua-Yadé corridor, which has an international extension [38,39,40]. The orientation of the fractures is a critical factor in determining their potential hydraulic role. It is possible for fractures to be open in one direction and closed in another. The field campaign facilitated observation of the alignment of mylonites, thereby substantiating the existence of the fault in the headwaters of the Benoue stream.

The methodologies employed to obtain the geological and structural results presented in this study are consistent with those utilized by other researchers in the field of geological and lineament map updating [15,17,33] [34,41,42] [43,44,45] [46,48].

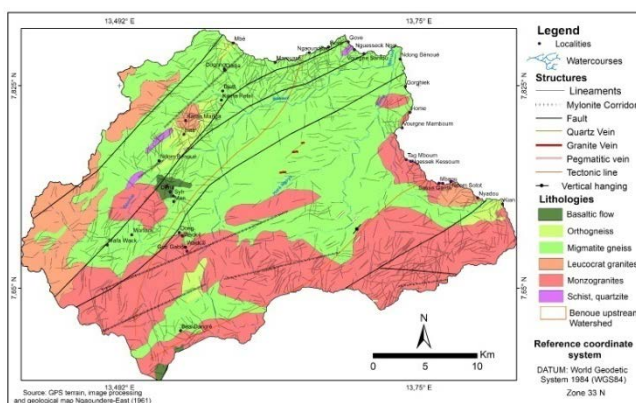


Figure 11. Updated geological map of the BUW

6. Conclusion

Geographic information systems (GIS) and remote sensing play a pivotal role in advancing geological studies. In this instance, the geological entities of lithology, tectonics, and magmatism are elucidated through the presentation of vector-based information layers. This is achieved through the acquisition, processing, analysis, and interpretation of Landsat 8 images, as illustrated in figure 9, 10, and 11. This has enabled us to more accurately delineate the geological contours of the various formations and to more precisely identify the lineaments. This process has enabled the updating of the BUW geological map and the establishment of a correlation between

aquifer production and the geological nature of the area. In terms of geology, three principal formations have been identified and mapped, exhibiting a range of facies: gneissic formations, granitic formations, and schist formations.

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