

Application of Remote Sensing for the Mapping of Geological Structures in Rainforest Area: A Case Study at the Matomb-Makak Area, Center-South Cameroon

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Abstract In the areas with rainforest vegetation, the use of SRTM (Shuttle Radar topography Mission) data because of their penetrative characters, high quality and availability, offers a new approach for the detection and interpretation of the geological structures. This paper presents the new structural mapping results of the Matomb-Makak area (western part of the Pan-African Yaound é series), based on the combined field survey and satellite image processing methods. The study area is characterized by dense forest vegetation with difficult access, scarcity and discontinuity of the available outcrops. As a consequence, geological mapping in this type of environment is difficult, time-consuming, expensive, and even dangerous and not accurate. During the field work, 280 outcrops have been investigated in which five main lithological units have been distinguished. In order to identify the foliation trajectories and the fractures network of kilometeric scale, the techniques of remote sensing were used. The processing of SRTM data led to the detection of linear anomalies. These anomalies have been verified and validated to structural map on the basis of field data. The analysis of the structural map indicates: (1) two directions of S_2 foliation (NE-SW major direction, locally folded and NW-SE secondary direction), (2) one family of faults trending NW-SE which locally displace the foliation, (3) a ductile shear zone with NNE-SSW trends which deflects the S_2 foliation. The two directions of foliation observed in the Matomb-Makak area as well as the NW-SE direction of fault are similar to those observed in the Yaound é series by other authors. However, the structural map obtained from the interpretation of field data is quite different to that obtained from remote sensing. We have noticed that the folding structures resulting from the interpretation of the field data are not observed on the structural map obtained from the interpretation of satellite image processing. Thus, the mapping of foliation trajectories in the rainforest area on the solely basis of the field measurements, is most of the time, an extrapolation which does not represent the structural architecture at regional scale. It is concluded that the combination of field-based mapping and remote sensing methods are useful tool for the mapping of geological structures within the densely vegetated regions of southern Cameroon.

Keywords: remote sensing, geological structures, foliation trajectories, rain forest area, cameroon

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1. Introduction

During the last two decades, many works have been carried out with the aims to better constrain the tectonic evolution of the Pan-African Central Africa fold belt (CAFB). For example, Nzenti et al. [1] and Toteu et al. [2] have subdivided the CAFB in Cameroon into three main litho-tectonical domains namely: (i) the northern domain, (ii) the central domain; and (iii) the southern domain. The southern domain covers the center-south of the country and is located in equatorial rain forest zone. This domain is made up of several lithological units which formed the Yaound é group. The Yaound é group is made up of three

series: the Yokadouma series [3], the Ayos-Mbalmayo-Bengbis series [4,5] and the Yaound é series [5,6]. Till date, these works were restricted to the areas with easier access and therefore could not provide a satisfactory explanation of the evolution of the Pan-African fold belt in Cameroon at large scale. Concerning the western part of the Yaound é series, some mapping works using field-based method have been carried out recently [6,7], but no accurate structural map was made.

The Matomb-Makak area belongs to the western part of Pan-African Yaound é series (Figure 1b). This area is characterized by densely vegetation and the scarcity of the outcrops. The access to the site is difficult and even dangerous. As a consequence, geological mapping in this

type of environment is difficult, time-consuming, expensive, and when possible, not accurate. Moreover, the available outcrops are most of the time discontinuous and unexploitable due to the strong degree of weathering. All these factors constitute a major problem for the accurate

geological mapping in the rain forest area. Recently, remote sensing has been largely used for geological mapping around the world (e.g: Southern Madagascar [9]; Central Eastern Desert of Egypt [10]; Mayo Kebbi in the SW of Chad [11]; Centre-South of Ivory Coast [12]).

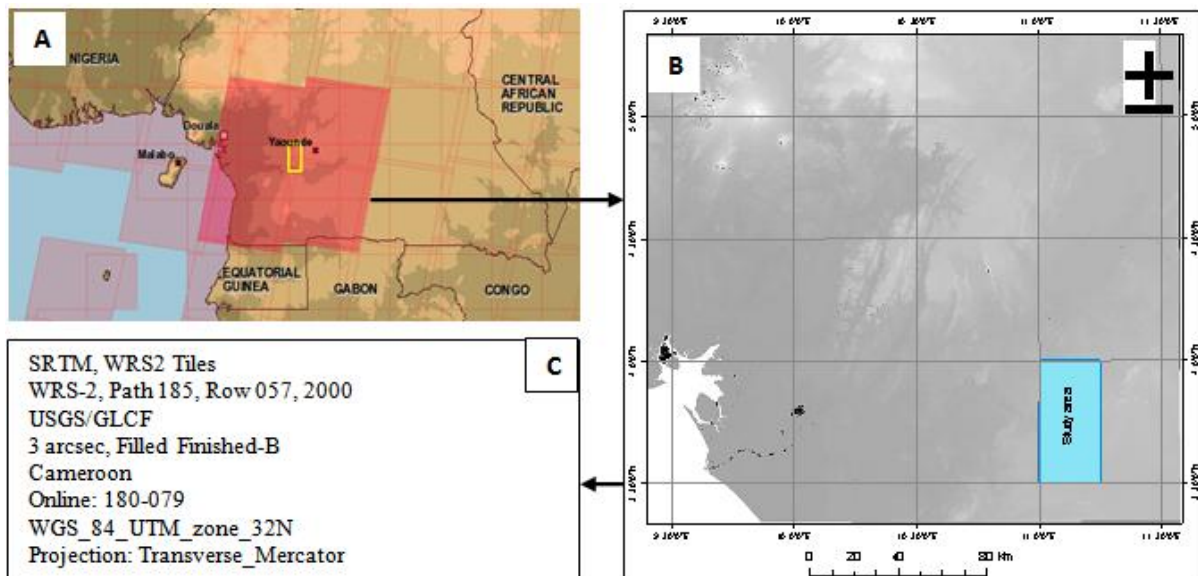


Figure 1. A) Location map of the center-south Cameroon rain forest domain showing the area covers by the satellite image use in this study; B) Raw SRTM image showing the location of the study area (blue box); C) Main characteristics of SRTM data used in this work

In this paper, a combination of SRTM (Shuttle Radar topography Mission) data processing and field-based survey methods have been used for the mapping of geological structures at Matomb-Makak area. The objective of this research was to show how the mapping method integrating remote sensing is useful for accurate interpretation of geological structures. This new mapping approach has enabled us to improve the mapping of lithological units and geological structures and therefore, has led to constraint the tectonic evolution of the Pan-African Yaoundé group in Cameroon.

2. Geological Setting

The Yaoundé series is mainly made up of granulites, migmatites and schists. These rocks are organized into two lithological units: (i) the metasedimentary unit is composed of kyanite-garnet gneiss, garnet-plagioclase gneiss and garnet micaschist with intercalation of calc-silicate rocks, quartzite and talcschist. Their protolith corresponds to the sedimentary rock with clay-carbonate composition (sequence rich in shale, greywacke, dolomite and evaporite) with interstratified basic volcanic layers [5-7,13]; (ii) the meta-igneous unit is formed by pyriclases, pyroxenites and talcschists [8,14]. The talcschist rocks are interbedded with the metasedimentary unit in some parts of the series [8].

On the structural point of view, the rocks of the Yaoundé series are characterized by a polyphase deformation with monocyclic tectonic evolution [5]. Four phases of deformation have been distinguished [15]: the D_1 and D_2 phases are two major events of ductile deformation. The D_1 phase is prior to the emplacement the dioritic calc-alkaline rocks and is responsible for the emplacement of nappes which have lead to high pressure

metamorphism, in granulite facies metamorphic conditions, of soft sediments. The D_2 phase is representative of a symmetric extension probably associated to boudinage of the foliation at large scale and (or) plate. The D_1 and D_2 deformational phases have been affected by D_3 and D_4 folding phases. The conditions of paroxysmal metamorphism are evaluated at 650-800 °C and 9.5-12 Kb [4,8,13,16].

The age of the granulite facies metamorphism as well as the calc-alkaline plutonism is 620 Ma [13,17,18]. Sm-Nd isotopic data indicate that the protolith of the rocks from the Yaoundé series is composed of a mixture of Neoproterozoic and Paleoproterozoic sources [17,19,20,21].

3. Results

3.1. Field Survey

The Matomb-Makak area covers a surface of about 1512 km² in which 280 rock exposures have been discovered and investigated during the field work. Rocks crop in the form of blocks, domes, road-cuts and flagstones. Field investigations have consisted of exploring the outcrops, measuring the geological structures such as foliation, lineament, folds, boudins, and fractures, and collecting representative sample of each rock types. Geometric analysis has consisted to describe and define the different deformational phases as suggested by Hobbs et al. [22].

Five main rock types namely garnet-chlorite schists, garnet amphibolite, garnet micaschists, talcschists and garnet-kyanite migmatite, have been distinguished. Based on the relative chronology of the different structural elements observed on the outcrop and the geometric relationship between these structural features, four main

phases of deformation have been defined. The D_1 phase is related to lithostatic pressure due to the weight of the sediments and to the tectonic compressional forces caused by the closure of the basin, and it is associated with the development of composite $S_0/S_1/S_2$ fabrics (Figure 2a). The D_2 tangential phase [5], responsible for the thrusting of the Pan-African nappes onto the Congo craton, is the major deformational event in the study area. This phase is characterized by a structural diversity and at cartographic scale, by a late- D_2 symmetric extension probably associated to the boudinage of the S_1 foliation at large scale, similar to that observed in the Yaoundé city [23]. During D_2 phase, the following structural elements have been developed:

- the S_2 foliation is outlined by a lithological banding (Figure 2a) and by a compositional banding (Figure 2a). S_2 foliation is locally folded, boudinated or sheared. In general, two main orientations of S_2 foliation have been identified: (i) a major NE-SW direction with average dips of 30 SE, 28 SE or NW and 15 SE or NW, recorded respectively in garnet amphibolite, garnet micaschist and garnet-kyanite migmatite; (ii) a less representative E-W to NW-SE direction observed in garnet-chlorite schist has an average dips of 28° towards the N, NE or SW;

- the B_2 boudins are developed in garnet-kyanite migmatite, garnet-chlorite schist and garnet micaschist.

They are underlined by quartzofeldspathic layers, sheared quartzites (Figure 2b) and amphibolite lenses respectively. They trend NNE-SSE to NE-SW;

- the L_2 lineation is mainly a mineral lineation formed by alignment of kyanite crystals in garnet-kyanite migmatite, muscovite and biotite lamellas in micaschist, chlorite flakes in the garnet-chlorite schist, and amphibole rods in garnet amphibolite (Figure 2c). It is sub-horizontal (3 to 20°) with NE-SW trends. The NW-SE trending L_2 lineations were also observed with a gentle plunge (0 to 20°) towards the NW;

- the P_2 folds have variable morphologies. They are either kink folds, either dissymmetric upright folds with sheared limbs (Figure 2d) or recumbent folds. The attitude of the P_2 folds axes is variable, and lies between N090E 10W and N180E03N;

- C_2 shear zones are rare. They are observed in garnet-kyanite migmatite where they are marked by quartzofeldspathic veins which transposed S_1 foliation with either dextral or sinistral shear movement;

The D_3 phase is mainly a shearing phase. It is composed of S_3 schistosity, L_3 lineation and C_3 shear zones (Figure 2d). The brittle D_4 phase is characterized by various orientated joints and veins.

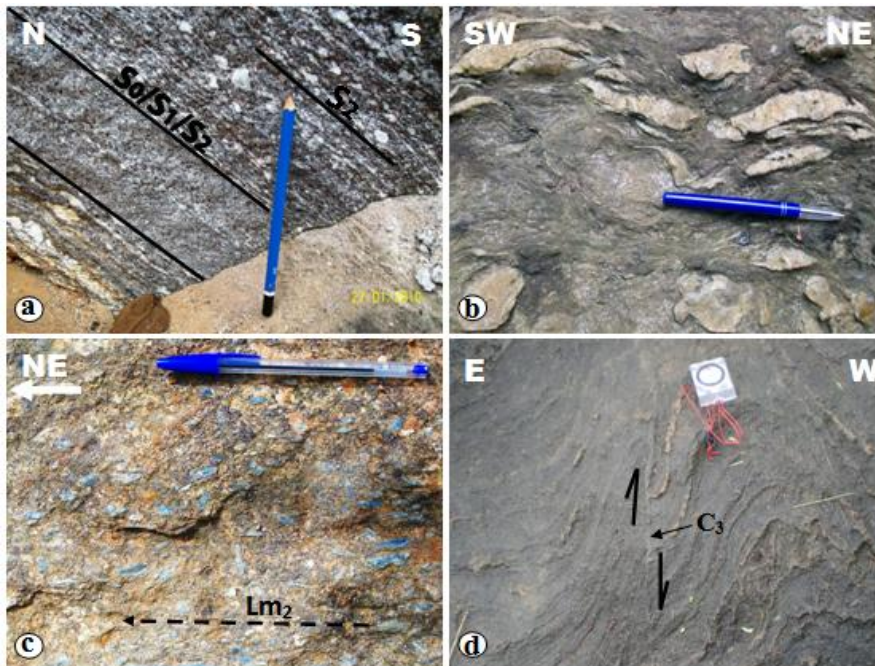


Figure 2. Structural elements observed in the studied area. (a) $S_0/S_1/S_2$ foliation in the garnet-kyanite migmatites of Nkenglikok; (b) quartzitic boudin structures in the garnet-chlorite schist of Makak, (c) L_2 mineral lineations in the garnet-kyanite migmatite of Hegba, (d) P_2 folding structures and C_3 shear planes at Hegba

3.2. Satellite Imagery Processing

SRTM images (scene 189-079; 185/057 Path/ Row; date of acquisition: 2000) of the center-South Cameroon area, were used for this work (Figure 1a). This scene is freely provided by USGS/GLCF (United States Geological Survey/Global Land Cover Facility) and directly downloadable in Geotiff format. The SRTM data have been imported into the ArcGis software where the study area has been delineated between the latitudes 3°30'N and 4°00'N and the longitudes 11°00' E and 11°15'

E (Figure 1b). This particular area was selected for two main reasons: (i) no detailed structural map is available till date, and (ii) the area is characterized by a diversity of petrographic units and structural elements which can provide insight for better understanding of the tectonic evolution of the CAFB in the Yaoundé series.

In this study, a series of image processing methods were used with the help of ArcGis software. The SRTM-DEM technique for structural interpretation is on the basis of shade relief image with various elevations [24]. In addition, the enhance techniques such as different vertical

exaggeration with varying sun azimuths and angles can improve elevation image for interpretation. In order to achieve the objectives, the following steps were undertaken: First, the raw SRTM images were classified and resampled using the cubic convolution method. Second, we proceed with a symmetrical inversion of the relief. The aim of this method is to determine surface linear anomalies. Third, shade relief images were created for various sun azimuths and angles. For this study, sun azimuths of 315° , 45° , 135° and 225° were used. The

different sun angle is able to map out the structures with various orientations (Figures 3a, 3b, 3c, 3d). Areas perpendicular to the sun angle are illuminated the most while the area with high angle or greater than 90° are shaded. This image enhancement method enables us to precisely map out the linear pattern. Figure 4 is the synthetic lineament map of the Matom-Makak area obtained from the different sun illumination azimuths. However, all the penetrative lineaments (fault) are not visible with this method.

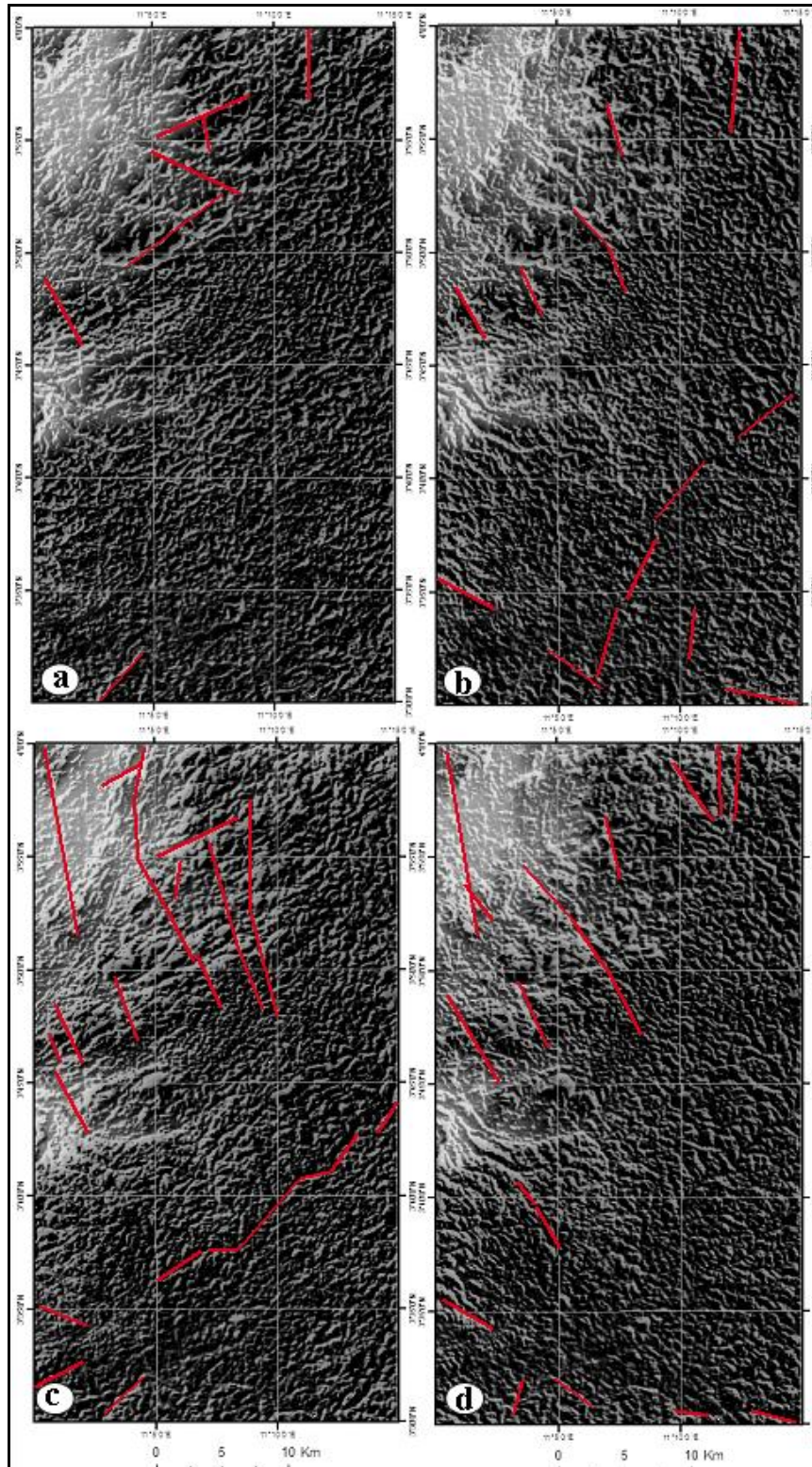


Figure 3. Example of shade relief image with varying sun azimuth and angle used to enhance structural determination of lineaments in the area. a) sun illumination azimuth at 315° ; b) sun illumination azimuth at 45° ; c) sun illumination azimuth at 135° ; d) sun illumination azimuth at 225°

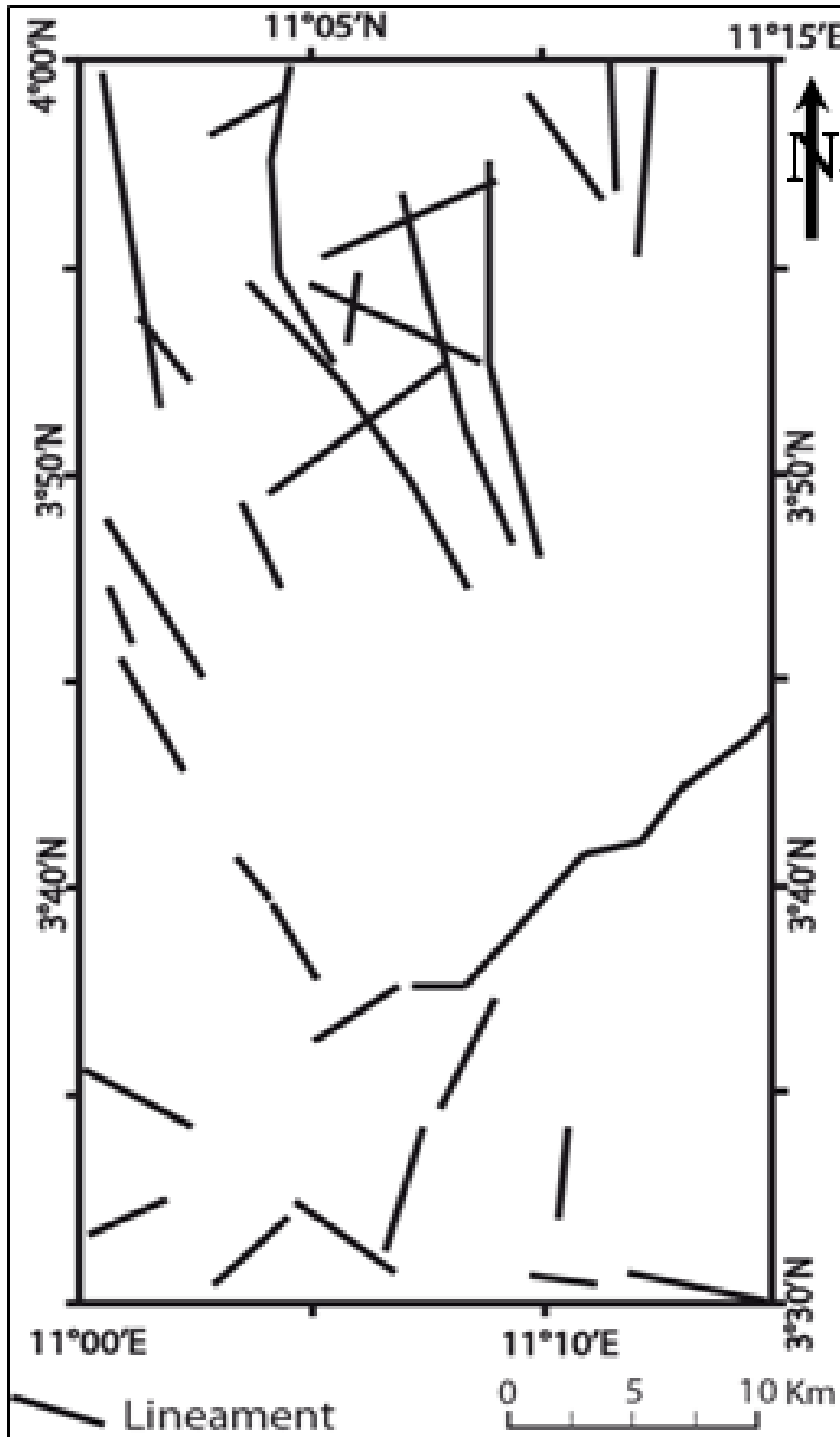


Figure 4. Synthetic lineament map of the Matomb-Makak area

In order to visualize all the geological structures (foliation, shearing and fault), the directional filters of SOBEL and Gradient NW have been applied. The use of 'Sobel vertical Operator' led to the visualization of a various continuous linear patterns (Figure 5). The disadvantage of this mode of image filtering is that it does not permit to differentiate the various types of structural elements. To solve this problem, the enhance images were combined using RGB (Red, Green, Blue) combination

mode and then we combined the two filters (Sobel horizontal directional filter and Gradient NW directional filter) to obtain the new enhance image. This new image has been filtered again using Sobel vertical Operator. This makes the geological structure determination easier. The foliation trajectories appear discontinuous and the faults become clearly visible and detectable by the straight lines which crosscut the foliation (Figure 6). This result, associated with field data, allows the accurate digitization

of the foliation trajectories and faults, using Adobe Illustrator software (Figure 7). On the map of Figure 7, the following geological structures are identified: (1) a family of fault oriented NW-SE, (2) two directions of S_2 foliation (a predominant NE-SW direction and less developed NW-SE direction), (3) a ductile shear zone with NNE-SSW trends located in the NW of study area. This shear zone of

cartographic scale was confirmed on the field where it is outlined by the deflection of S_2 foliation planes in the garnet-kyanite migmatite. The combination of the remote sensing results and the field survey data has enabled us to obtain the detailed structural map of the Matomb-Makak area (Figure 8).

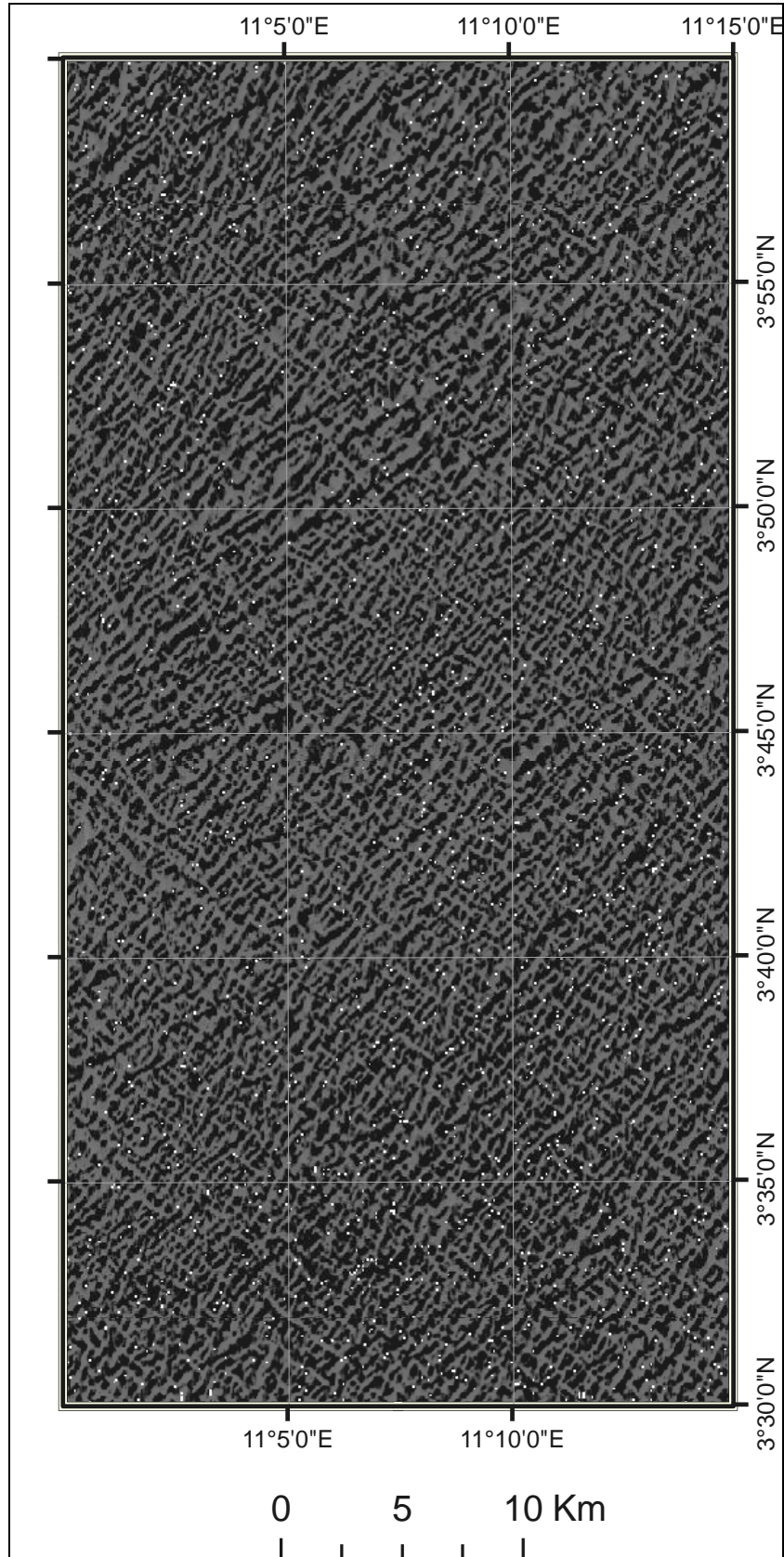


Figure 5. Enhanced SRTM image of Matomb-Makak area obtained from NNW sun illumination and the SOBEL directional filter

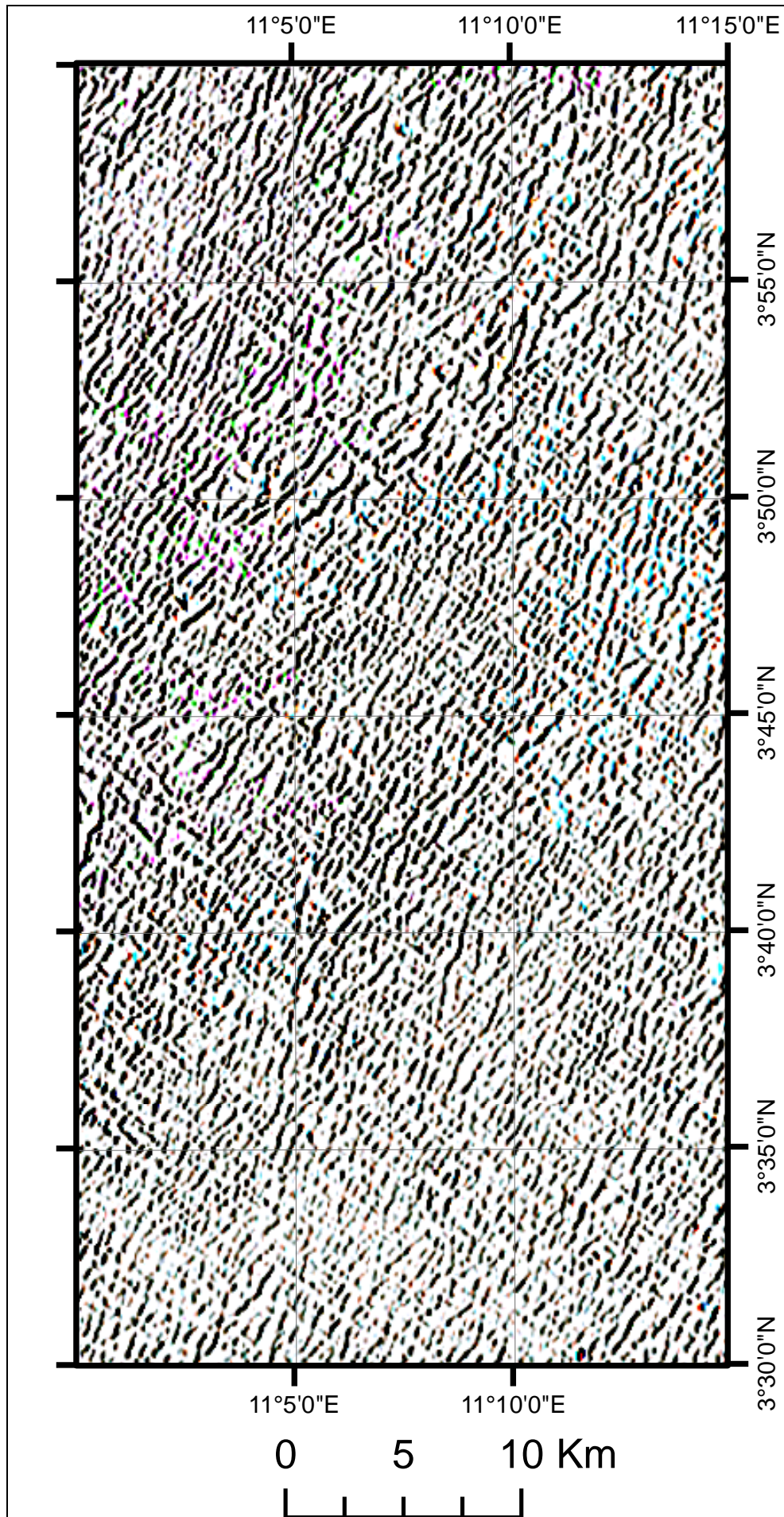


Figure 6. Enhanced SRTM image of Matomb-Makak area obtained from NNW sun illumination and the SOBEL directional and Gradient NW filters

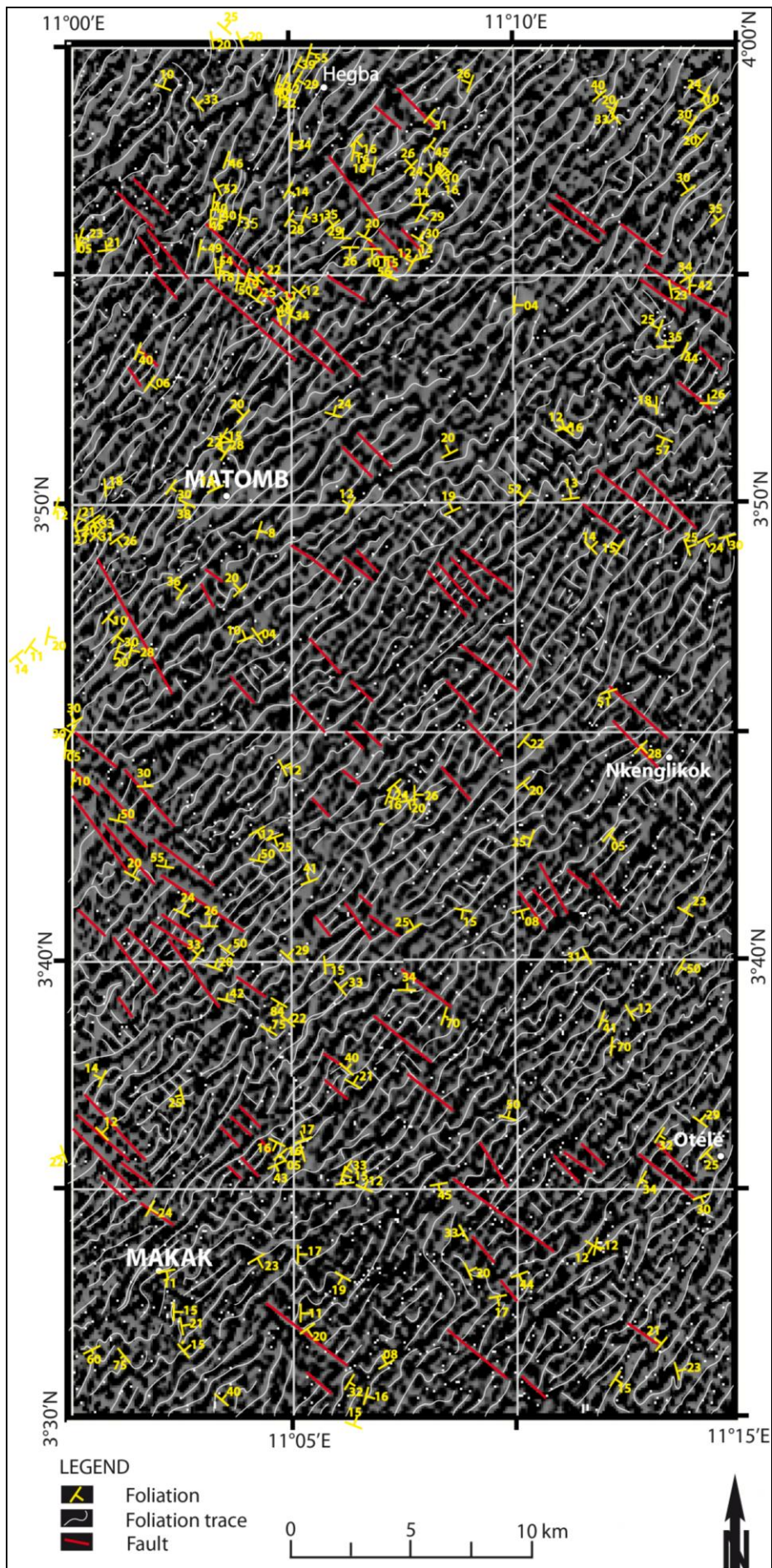


Figure 7. Superposition of filtered image (gray background), digitized layer of foliation trace (white curves), faults (red lines) and field data (yellow symbols and value)

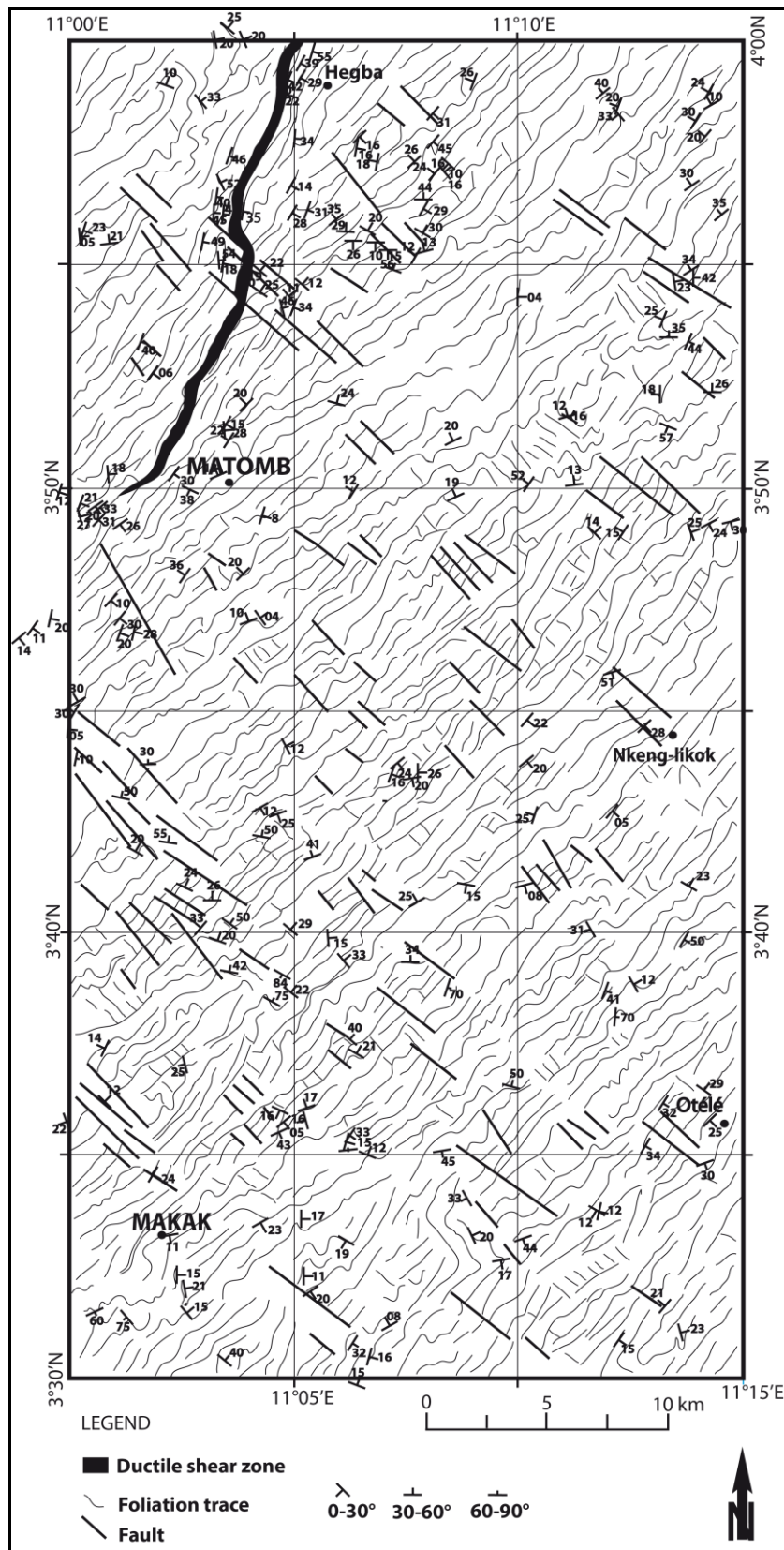


Figure 8. Structural map of the Matomb-Makak area obtained from the combined field-based and remote sensing methods

4. Discussion

Remote sensing has been largely applied for structural mapping around the world. For example, Schetselaar et al. [25] have contributed to the lithological mapping of Mozambique by the SRTM and Landsat ETM⁺ images processing. Using Landsat TM data, Randrianasolo [9] has

successfully mapped the geological structures of the southern Madagascar. Moussa Isseini [11] has used Landsat ETM⁺ data to map the lithological unit and the geological structures of Mayo Kebbi area, SW of Chad and part of East and Far North Cameroon. Piyaphong [24] with the help of the DEM (Digital Elevation Model) data has discovered a NW-SE trend fault system with dextral movement at Koh Samui in the gulf of Thailand.

Nowadays, it clearly appears that the use of remote sensing for the geological mapping became an indispensable tool for the realization of the detailed and precise geological map.

In Cameroon, the geological mapping using remote sensing method is not yet developed. The Matomb-Makak area, located in rain forest domain of Cameroon, is a good target for the application of remote sensing especially SRTM data because of their penetrative character. Geological structures, especially the foliation trajectories obtained by SRTM image processing, locally matched those observed on the field. However the map obtained from the field-based mapping (Figure 9a) is different from that obtained from the combination of the field data and remote sensing results (Figure 9b). We have explained this

situation by the fact that the outcrops are discontinuous on the field and the measures taken on structural elements were not enough. Thus foliation trajectories resulting from these measures represent an extrapolation which does not always reflect the entire field realities, as shown in Figure 9b. The interpretation the foliation trajectories on the simply basis of the field data is commonly used by the geologists. The field-based structural mapping is efficient in the areas with abundant and continuous outcrops (eg.Saharan area). In rain forest area, because of the scarcity and discontinuity of the outcrops, this mapping method is limited and when it is used; their interpretation is only valid for the particular area where the measures were taken of the geological structures, i.e. without regional significance.

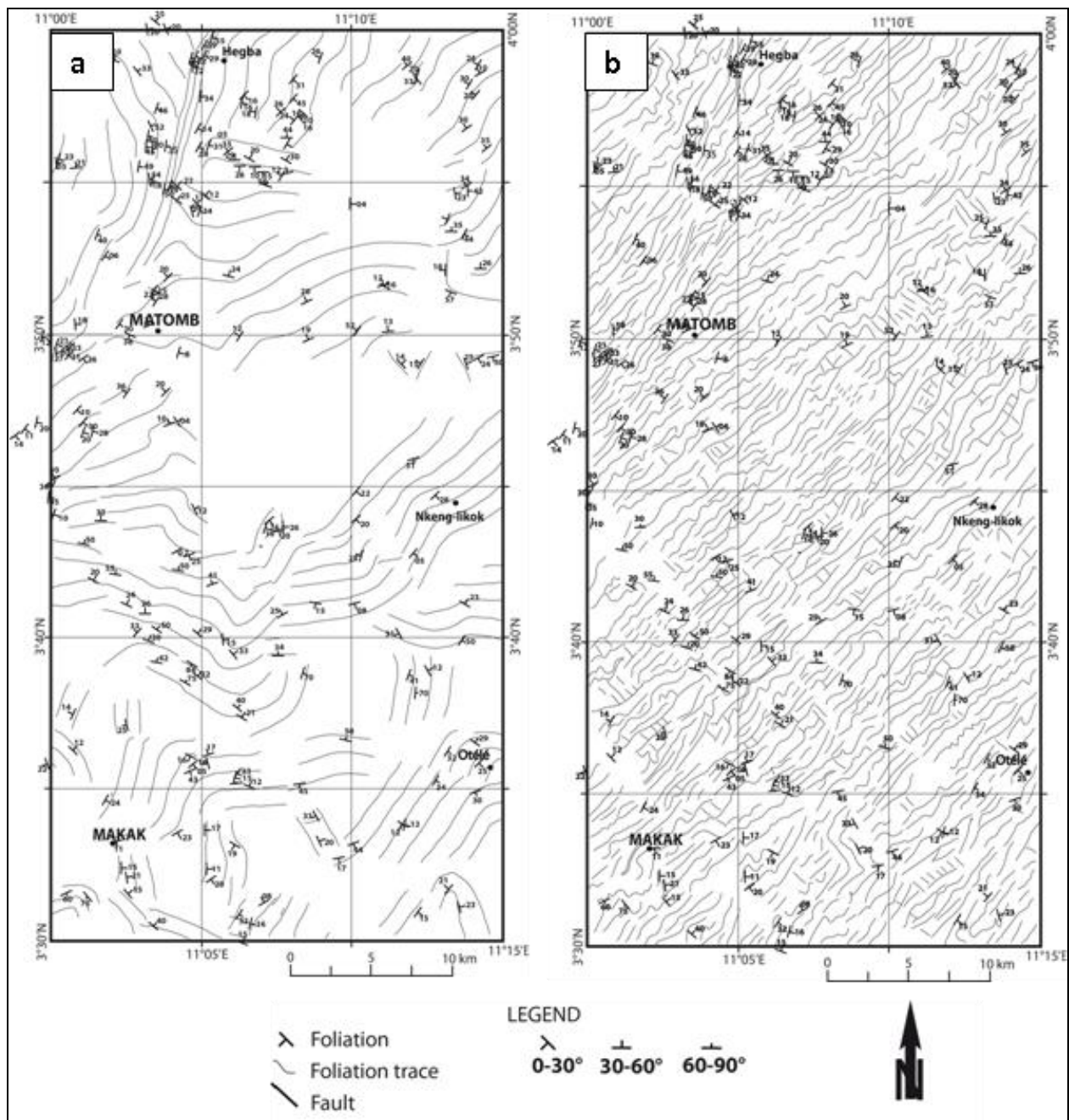


Figure 9. Comparison between the field-based structural map (a) and the combined field-based and remote map (b)

The two directions of the foliation observed in the Matomb-Makak area are similar to that obtained in the Yaoundé series by other authors (e.g. [8,13,15]). However

these authors have interpreted this structural disposition as result from the folding of the foliation at regional scale. The new results obtained from this study have confirmed

the existence of folding structures in the Yaoundé series, but reveal that these folds have only local importance (<1 km). The NW-SE trends family of faults map out in this work is similar to that observed in Yaoundé by Mvondo et al. (2007).

5. Conclusion

The SRTM image processing combined with field survey of the Matomb-Makak area have led to the construction of a detailed structural map on which the following informations were highlighted: (i) two directions of S_2 foliation (NE-SW major direction, locally folded and NW-SE direction less pronounced), similar to those observed in the Yaoundé migmatites; (ii) a local scale folding with axis oriented N-S to NE-SW, (iii) one family of faults trending NW-SE that locally displaces the foliation, (iv) a ductile shear zone with NNE-SSW trends affecting the garnet-kyanite migmatites. This shear zone is responsible for the deflection of S_2 foliation.

However, the field-based structural map is quite different to that obtained from remote sensing. We have noticed that the folding structures resulting from the interpretation of the field data are not observed on the structural map obtained from the interpretation of satellite image processing. Thus, the mapping of foliation trajectories in the rainforest area on the solely basis of the field measurements, is most of the time, an extrapolation which does not represent the structural architecture at regional scale. It is concluded that the combination of field-based mapping and remote sensing methods are useful tool for the mapping of geological structures within the densely vegetated regions of southern Cameroun.

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