Hydrology
2022; 10(4): 65-74
http://www.sciencepublishinggroup.com/j/hyd
doi: 10.11648/j.hyd.20221004.11
ISSN: 2330-7609 (Print); ISSN: 2330-7617 (Online)

Fracturing and Hydrogeological Potentialities of the Gneisso-Migmatitic Units Along the Keve – Amoussoukope Road in the Southwest of Togo (West Africa)

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To cite this article:

Kodjovi Zondokpo, Mahaman Sani Tairou, Alassani Arouna Mouhamad Bang'na, Masamaeya Dadja-Toyou Gnazou. Fracturing and Hydrogeological Potentialities of the Gneisso-Migmatitic Units Along the Keve – Amoussoukope Road in the Southwest of Togo (West Africa). *Hydrology*. Vol. 10, No. 4, 2022, pp. 65-74. doi: 10.11648/j.hyd.20221004.11

Received: September 29, 2022; **Accepted**: October 20, 2022; **Published**: October 28, 2022

Abstract: In this study, photogeology is coupled with pre-existing well data to examine the impact of lineaments on aquifer productivity in an area where access to potable water is a serious challenge. The photogeological study of the peneplain portion along the Keve - Amoussoukope (SW-Togo) road has revealed a dense lineament network mainly represented in the NNE-SSW (N10-N20), NE-SW (N30-N50) and ENE-WSW (N60-N80) directions. The network components are dominated in number and weight (cumulative length of lineaments or fractures in a given direction) by the NE-SW lineament family. The brittle tectonic data from the field and the geological map confirm the network characteristics and validate the fracturing state of the gneisso-migmatitic formations belonging to the internal units of the Panfrican Dahomeyides Belt (600 ± 50 My). The lineament or fracture network density confers discontinuous aquifer properties to the gneisso-migmatitic formations in the study area. In fact, the major lineament and well coupling shows that wells with high flow rate ($Q > 5\ m^3/h$) are associated with the NE-SW dominant lineament network. Statistical analysis established with well data in the area highlights a large variation in productivity of the wells, probably linked to the lithological heterogeneity.

Keywords: Lineaments, Fracture Aquifer, Gneisso-Migmatitic Units, Dahomeyides, South-west Togo

1. Introduction

According to the Togolese Ministry of Water, nearly 40% of the population lacks access to drinkable water. This is an obstacle to achieving the sixth sustainable development goal. Depending on hydrological and environmental conditions, this problem of access to drinkable water can become critical in some areas like the southwest of Togo which consists of basement rocks. In fact, this part of the area does not have perennial stream flows. The available surface water resources in the area are ponds often polluted by diverse anthropogenic activities. The rare large diameter water-wells dug in shallow weathering cover dry up at the end of the rainy seasons. Consequently, the only alternative resource for the populations in the sector is ground water located in the gneisso-migmatitic basement. The potential of this aquifer type depends on the state of rock fracturing [22, 30]. This explains the implantation of "rural hydraulic" wells in many localities since the 1950s.

Without a good knowledge of the fracture locations and the level of their network development, any water supply project in the area might fail. The current selection methods of the well sites location lead to high number of negative wells.

This research seeks to contribute to better understanding of the hydrogeological potential of the gneisso-migmatitic formations in the part of the peneplain located along the Keve - Amoussoukope road. More specifically, it characterizes the lineament network in the area and makes a connection between the spatial distribution of wells and their productivities.

2. Study Area

2.1. Geological Overview

The geological context of this study concerns a portion of the Dahomeyides internal zone frontal part (Figure 1).

The Dahomeyides orogen results from collision between the eastern margin of the West African Craton (WAC) and the Benino-Nigerian shield, 600 ± 50 My ago [3]. It is defined as a nappe pile thrust over the Volta Basin [29]. The western nappes (external zone) regroup tectonized and metamorphosed equivalents of the lower and middle supergroups (Bombouaka and Oti Supergroups) of the Volta Basin [2, 26]. They tectonically carry the granulitic and sometimes eclogitic nappes found in the submeridian massif string constituting the suture zone. The Dahomeyides internal zone covers the peneplain starting from the basic to ultrabasic massifs line (Derouvarou, in the NW of Benin, the Kabye, Kpaza, Djabatoure-Anie and Agou-Ahito, in Togo and the Akuse or Shai, in the SE of Ghana) up to Nigeria. It is defined as a set of gneisso-migmatitic units associated with meta-volcanosedimentary belts that are more and more invaded toward the east by panafrican granitoides [3, 7, 8, 10, 12]. These internal units represent the Metacraton or the Benino-Nigerian shield [1]. These are eburnean sets (2000 $\pm 150\ My$), that were widely remobilized during the panafrican orogenesis [15].

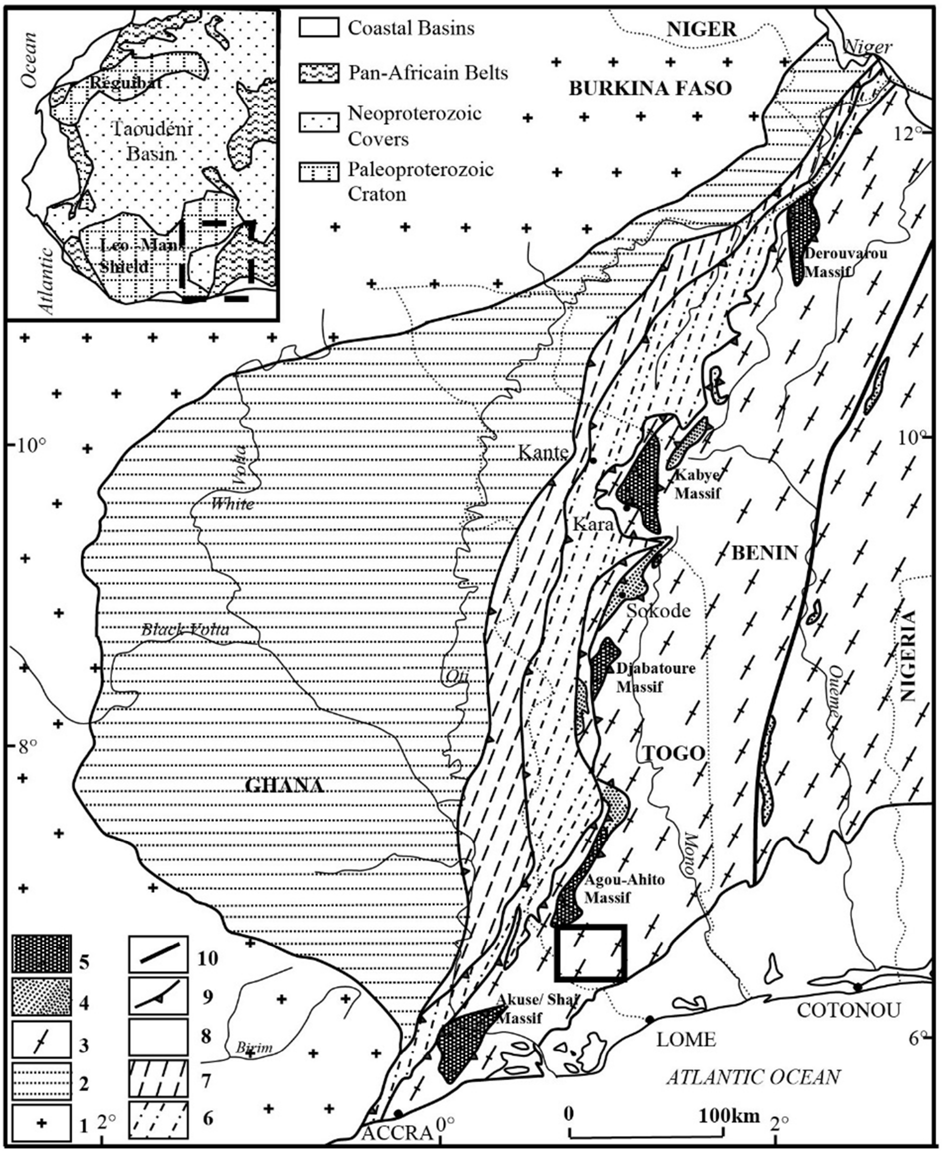

Figure 1. Location of the study area (framed) in the regional geological context ([29] slightly modified). 1 = eburnean basement of the Man - Leo shield (WAC); 2 = neoproterozoic to paleozoic cover of the Volta Basin; 3 = internal and external gneisso-migmatitic units; 4 = micaceous kyanite quartzites; 5 = basic-ultrabasic massifs of the suture zone; 6 = Atacora structural unit; 7 = Buem structural unit; 8 = Meso-Cenozoic basin of the Gulf of Guinea; 9 = thrust contact; 10 = Kandi fault mylonitic zone.

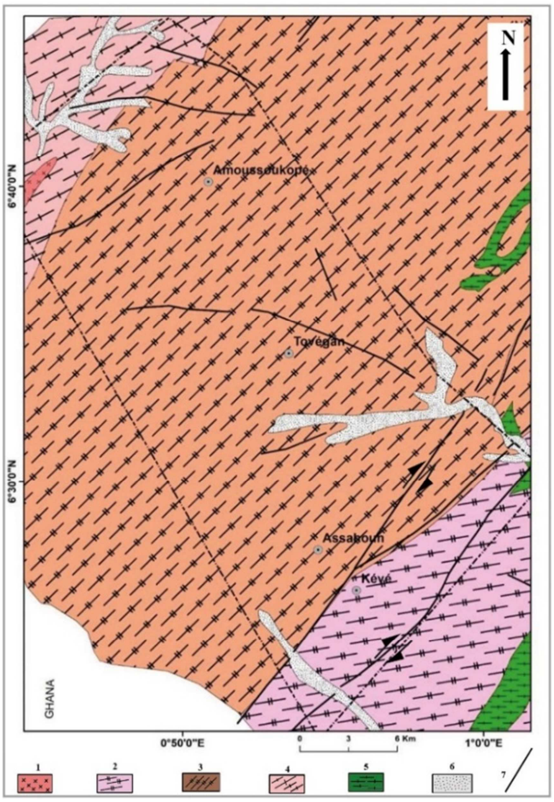

Figure 2. Extract of the geological map of [27] showing the main lithological components of the study area. 1 = orthogneiss and muscovite, biotite, biotite-amphibole or garnet metagranites; 2 = biotite $\pm$ *muscovite, biotite and amphibole migmatites; 3 = biotite* $\pm$ *muscovite migmatite; 4 = biotite muscovite gneiss; 5 = biotite amphibole gneiss; 6 = alluvium; 7 = Faults.*

According to [27], the peneplain in the southwest of Togo, lithologically includes various gneiss suites: 2-mica gneiss, amphibole biotite gneiss, amphibole, biotite and/or garnet metagranites and migmatites (Figure 2). These components outcrop sporadically in flattened domes or inselbeg relics (Figures 3a and 3b). Amphibolite enclaves of centimetric to metric size (Figure 3c) are often found in outcrop.

Structurally, the internal units of the Dahomeyides bear imprints of five panafrican deformation phases [9, 28]. The Dn phase, penecontemporaneous with the collision between the overthrusting plate of the Benino-Nigerian shield and the eastern border of the WAC, is materialized by a quasi-obliterated Sn foliation. The Dn+1 phase corresponds to an episode of nappe piling marked by the regional foliation Sn+1.

The last three phases (Dn+2, to Dn+4) are tightening phases or post-nappe folding associated with brittle tectonics [9]. These late phases bring to a close of the Dahomeyides orogen building.

2.2. Hydrogeological Framework

Hydrogeologically, the gneisso-migmatitic peneplain in the southwest of Togo contains two types of aquifers [13]: weathered rock and fracture aquifers. The first type corresponds to a generally clayey sand supergene weathered rock cover (Figure 4) often tapped by big diameter wells. The average thickness of this pedological cover is generally only a few meters, but it can be much greater in depressions [20].

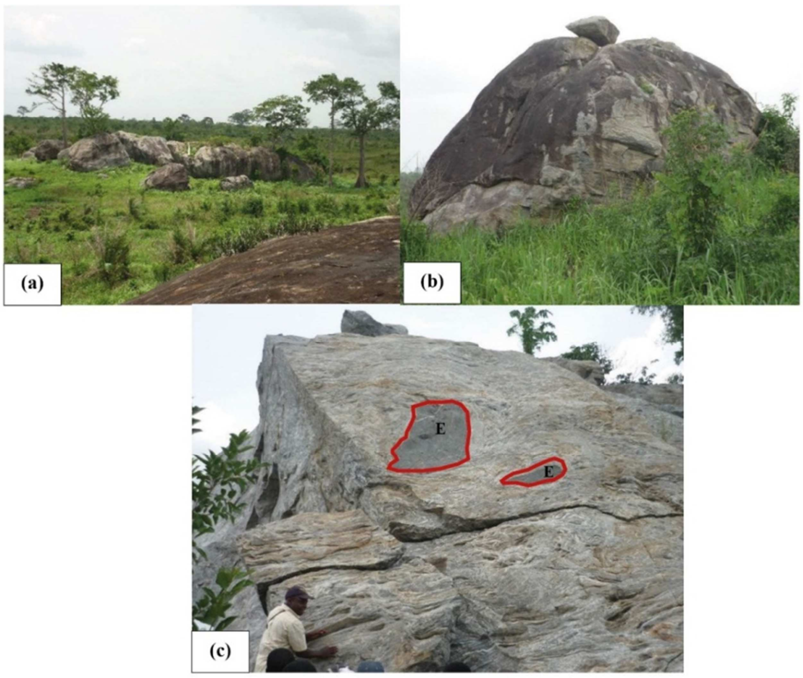

Figure 3. Some morphological and petro-structural aspects of the gneisso-migmatitic outcrops in the study area. (a) - Metric blocks and balls cluttering a large outcropping dome at Gokacope (N06°21'34.5" - E01°02'11.4"); (b) - Inselberg relic about 10 meters high at Agoudja (N06°23'01.6" - E01°02'12.9"); (c) - Remains of dome outcrop at the Glekope quarry (N06°42'27.1" - E00°40'03") showing dark amphibolite enclaves (E) contained in a biotite amphibole diatexite.

Fracture aquifers are represented by reservoirs in more or less fractured gneiss and migmatite [4, 9, 29]. The storage capacity of these rocks is defined by a secondary porosity (fracture porosity) stemming from the late episodes of panafrican brittle tectonics. These discontinuous reservoirs are those solicited by rural water drilling projects.

Figure 4. *Typical weathering profile of the gneisso-migmatitic formations in the study area.*

Finally, it is important to note the presence, on some outcrops in the area, of natural reservoirs resulting from rain water accumulation in alteration and erosion pockets of big amphibolitic enclaves (Figure 5). These structures, generally of varied shapes, are sometimes quite deep, and are exploited throughout the year by the people for their different needs including for domestic uses.

Figure 5. *Metric water reservoir at Gokakope. This water is covered by water lettuce (Pistia Stratiotes) and occupies a pocket resulting from the differential alteration and erosion of a big amphibolite enclave.*

2.3. Climate

Like all the Togolese meridional part, the Keve - Amoussoukope area has a subequatorial climate type with two dry and two rainy seasons. The rainy period runs from March to October, with a short interruption more or less pronounced in August and corresponding to the small dry season (Figure 6). Thus, the longer dry season covers the period from November to February. Precipitation maximums occur in June and September. Inter-annual pluviometry shows small variabilities with a mean of about 1550 mm.

Average annual temperatures vary between 20°C observed in August and 32°C in February. Moreover, temperature fluctuations over many years are low [30].

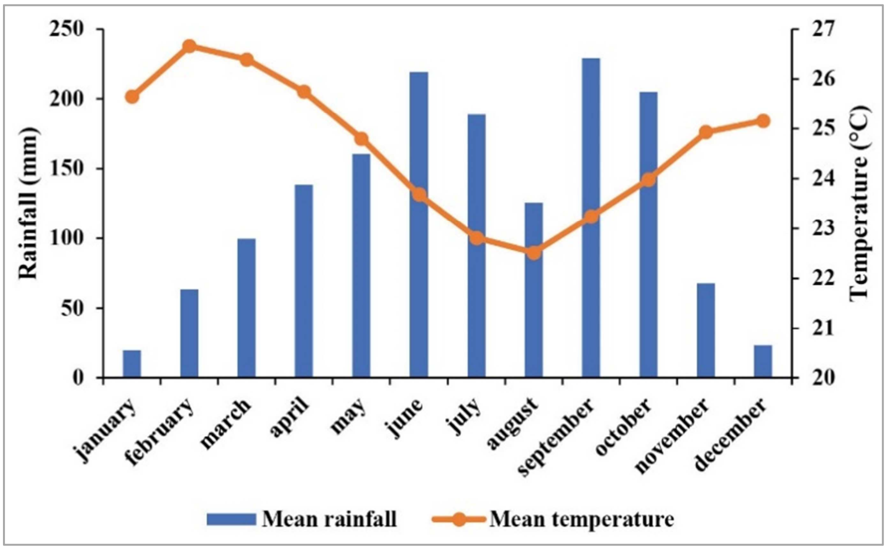

Figure 6. *Average monthly rainfall and temperature from 1996 to 2016 at the Kouma-Konda synoptic station located approximately 40 km northeast of the study area. (Data source: Togolese National meteorological Directorate).*

3. Method

To create the lineament map, aerial photographs (Mission 69 NB 31 XIII XIV) of the study area were analyzed using a mirror stereoscope. A set of 47 photographs (scale 1/30000) allowed using tracing paper to obtain the lineament network guided by numerous fracture indicators on the photographs [21, 25]. A mosaic of all the tracing papers is obtained in A3 format. The mosaic has been digitized and georeferenced using the ArcGIS and QGIS software. These operations resulted in an exhaustive mapping of the lineament network. The components of the network were defined by number and weight (cumulated length of fractures or lineaments in a given direction), using the Tectonics FP software (Version 1.7.9).

The lineament map was validated using field, and tectonic data from the geologic map [27].

The locations of 68 wells were plotted on the lineament map and correlations between the flow rate of wells and certain lineament parameters such as direction, length, and relative distance to the nearest well allowed to establish the link between well productivity and lineament.

4. Results

4.1. Characteristics of Lineament Network

The Figure 7a shows a dense network of hectometric to kilometric lineaments represented in all directions. Three main directions are distinguishable: NNE-SSW (N10 - N20), NE–SW (N30 - N50) and ENE-WSW (N60 - N80) (Figure 7b). In order to analyze the importance of diverse components of the network, the lineaments were distributed as a function of weight (Figure 7c). This distribution confirms the predominance of submeridian to NE–SW (N20 - N60) lineament families.

4.2. Validation of Lineament Map

By overlaying the lineament network on the geological map [27], it is evident that some identified fractures are similar to the photo-interpreted lineaments (Figure 8). Only the main shear corridors represented in the southeast part of the study area (Figure 2) do not appear on the aerial photographs.

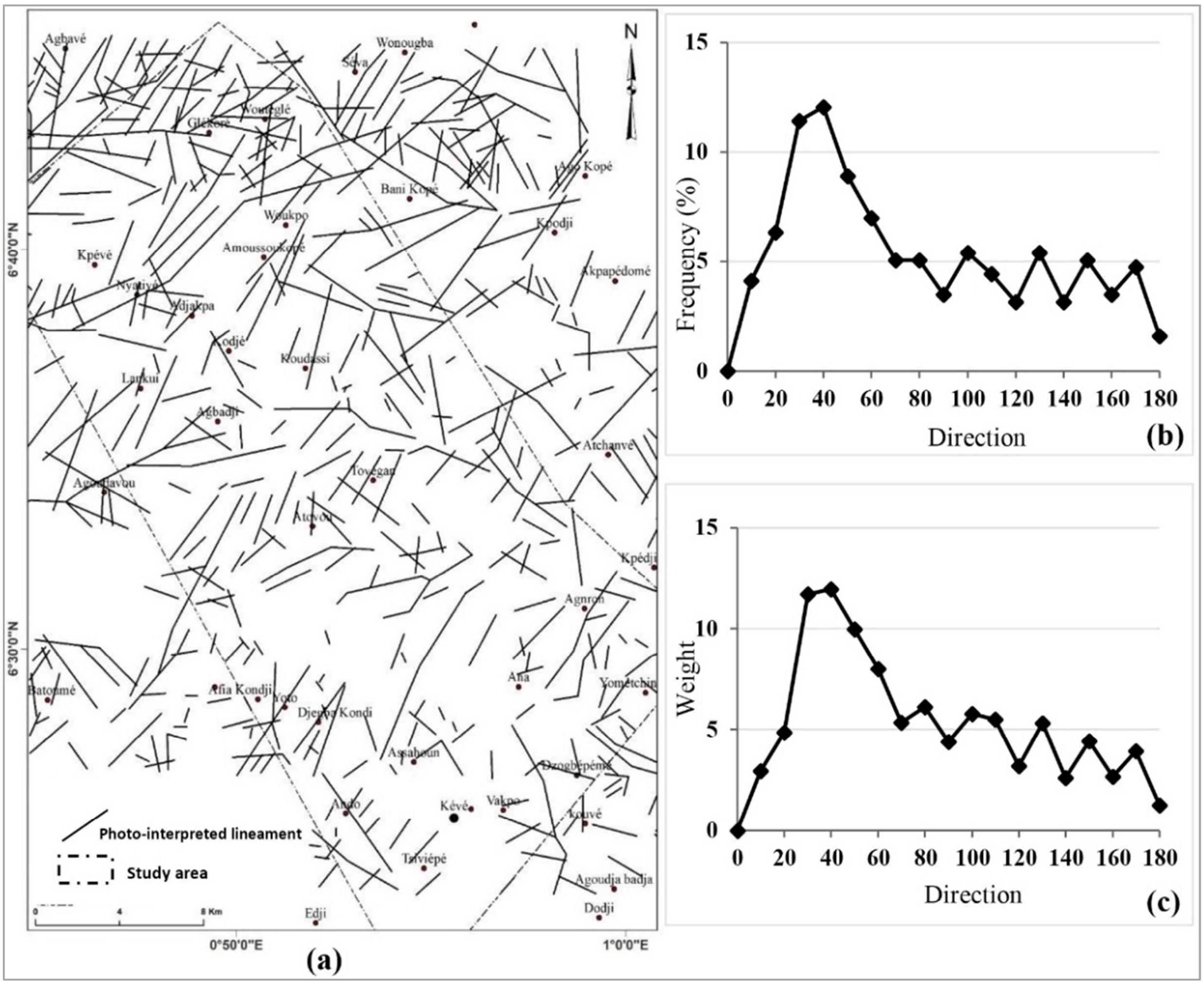

Figure 7. *Characteristics of lineament network in study area. (a) - Map of photo-interpreted lineament network, (b) - Distribution diagram of lineaments as a function of number, (c) - Distribution diagram of lineaments as a function of weight (cumulated length of lineaments or fractures in a given direction).*

From outcrop, the fracture planes sometimes look spectacular and trend mainly in a NE-SW direction (Figure 9a). In the quarries there are numerous striated planes defining families of panafrican strike slip faults (NE–SW to ENE–WSW dextral, NW–SE dextral or sinistral and NNE-SSW sinistral faults; Figure 9b).

On all the gneisso-migmatitic formations composing the basement of the Meso-Cenozoic basin in the south of Togo, [4] has underscored NNE–SSW to NE–SW (N20 - N40), NE-SW to ENE-WSW (N60 - N80) and NW–SE (N120 - N140) lineament components, with a clear predominance of the latter.

All these features recorded at aerial views and outcrop scales attest the significant fracturing of the gneisso-migmatitic formations that underlie the peneplain in southwest Togo.

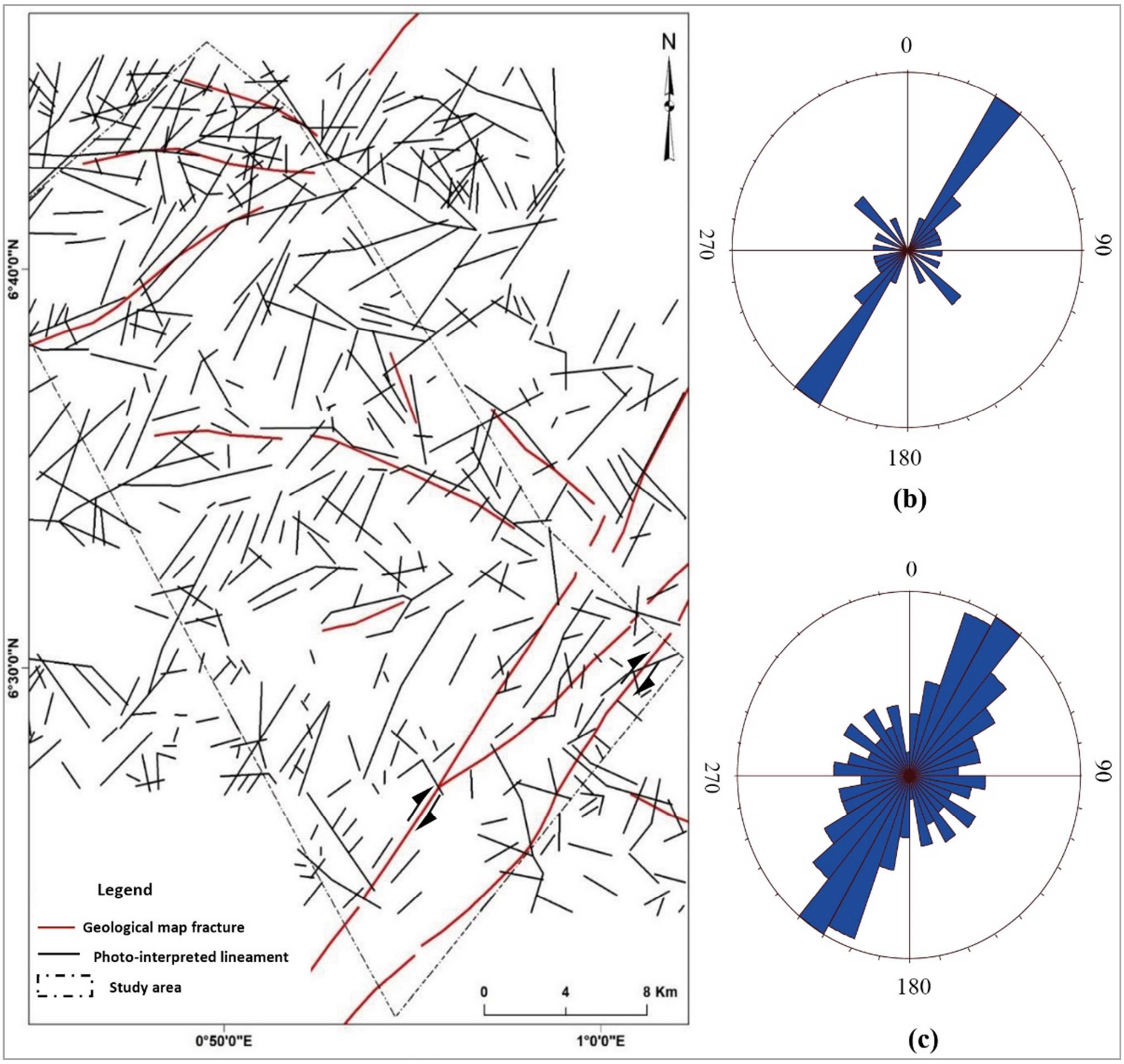

Figure 8. Validation of the lineament map. (a) - Lineament map superimposed on the fracture network extract from the geological map of Sylvain et al. (1986); (b) - Rose diagram of the directional synthesis of fractures on the geological map; (c) - Rose diagram of the directional synthesis of the photo-interpreted lineaments.

4.3. Evaluation of Hydrogeological Potential

The map coupling the major lineaments and well locations (Figure 10a) shows that, in general, the high flow wells are associated with lineaments or their intersections. This association is proof that the hydrogeological potential of the gneisso-mimatitic formations is linked to fracturing. In fact, many studies [6, 14, 16-19, 23, 24] have shown the relation between well productivity and their proximity to lineaments or fractures in the basement. Moreover, as shown in figure 10b, most of the major lineaments to which high flow wells are associated occur in the NE – SW (N30 - N60) directions.

Table 1 shows that the large majority of wells (92%) intersect kilometric lineaments. This wells have an average flow rate between 12 and 13 m^3/h. On the other hand, the remaining 8% of wells associated to hectometric lineaments give flow rate relatively low (9 m^3/h). This distribution is in line with the findings of the Interafrican Committee for Hydraulic Studies [5, 12]. Who demonstrated the importance of the fracture length parameter on productivity.

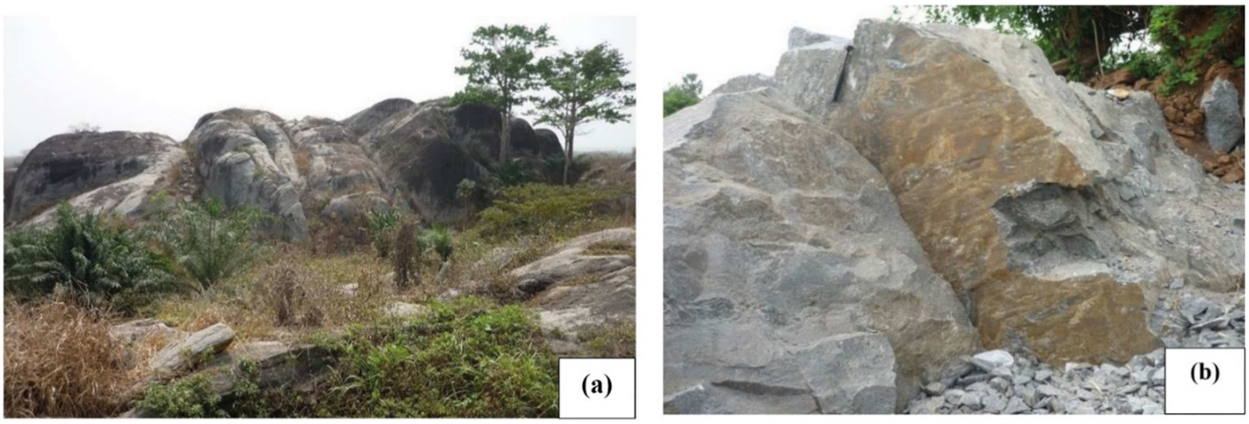

Figure 9. *Some aspects of fracturing at outcrop scale. (a) - NE–SW trending fractures cutting a major plane of a longitudinal fracture trending WSW-ENE at Agoudja (N06°23'01.6" - E01°02'12.9") (b) - NE-SW strike slip fault slickenside in quarry at Bagbe (N06°19'54" - (E01°00'39").*

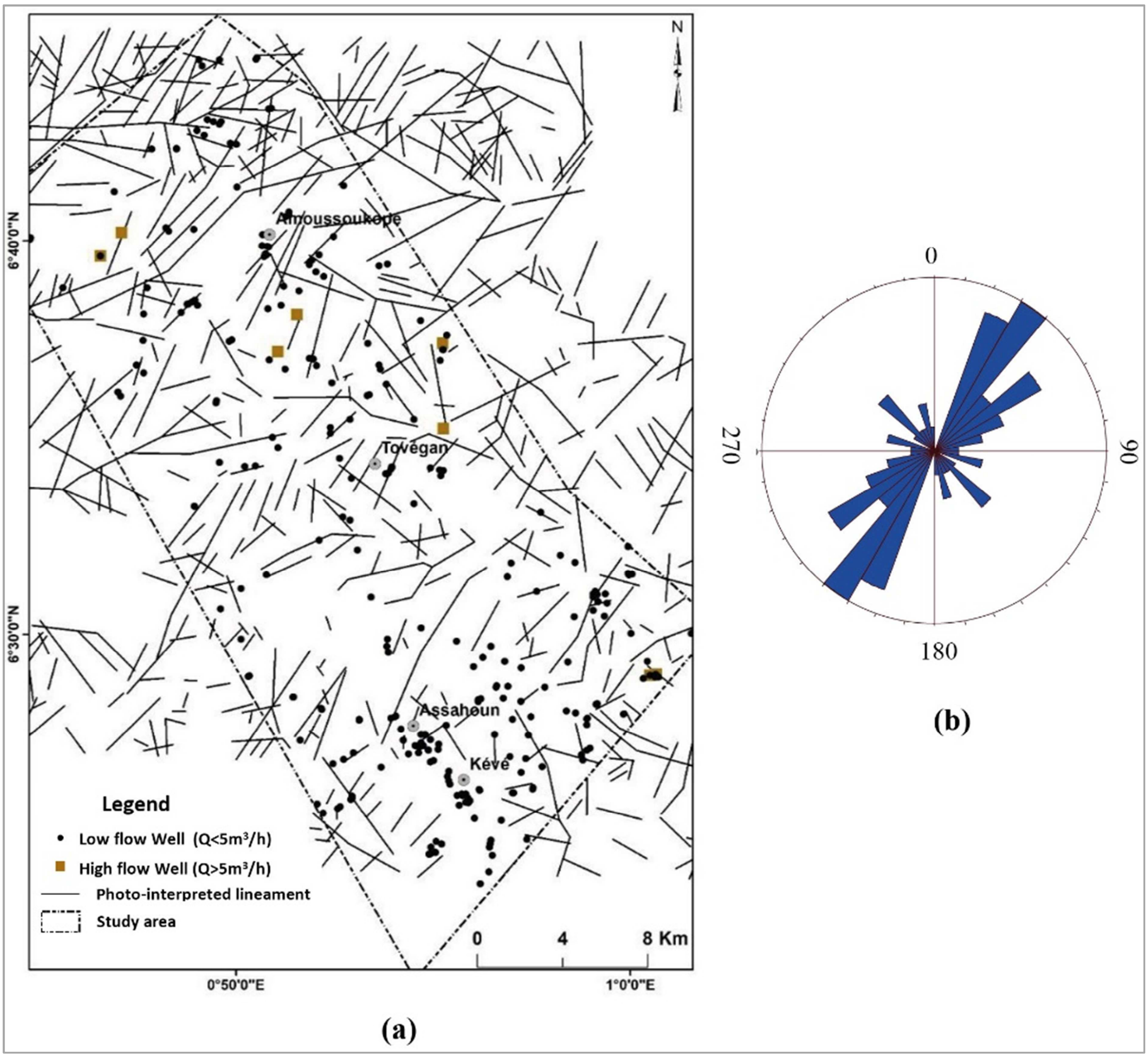

Figure 10. *Evaluation of the hydrogeological potential of the gneisso-migmatitic formations in the study area (a) - Map coupling major lineaments and wells; (b) - Rose diagram showing directional synthesis of the most productive lineaments or fractures.*

Table 1. *Distribution of high flow rate as a function of lineament length.*

Lineament length (m)	High flow (%)	Medium flow (m^3/h)
<1000	8	9
1000-2000	50	12
>2000	42	13

In order to evaluate rock formation productivity, the parameters (flow rate, depth) of 68 wells obtained from the Ministry in charge of water in Togo were analyzed. From this statistical analysis, it emerges that in the gneisso-migmatitic peneplain portion, in southwest Togo, the flow rates of wells deep from 35 to 118 meters vary between 0.2 and 27 m^3/h (Table 2). The significant variation in the flow rates of wells is probably a reflection of the heterogeneous nature of fracturing of the formations. Thus, the Tovegan migmatite (Figure 2), probably more fractured, appears to be more productive. This can explain the fact that the quasi-totality of the wells with high flow rates are found in it (Figure 10).

Table 2. *Analysis of parameters of wells implanted in the study area (Data source: Ministry in charge of water, Togo).*

Parameters	Minimum	Maximum	Median	Mean	Standard deviation	Coefficient of Variation
Flow rate (m^3/h)	0,2	27,0	2,1	4,4	5,7	1,3
Total depth (m)	35,0	118,3	61,6	66,3	21,8	0,3

Furthermore, considering the [11] classification, the majority of these wells (63.7%) occur in classes with very low or low flow rates (Figure 11). Only 36.4% of the wells in the study area give medium to high flow rates. This distribution of flow rates of wells attest to a non-negligible hydrogeological potential of the gneisso-migmatitic peneplain.

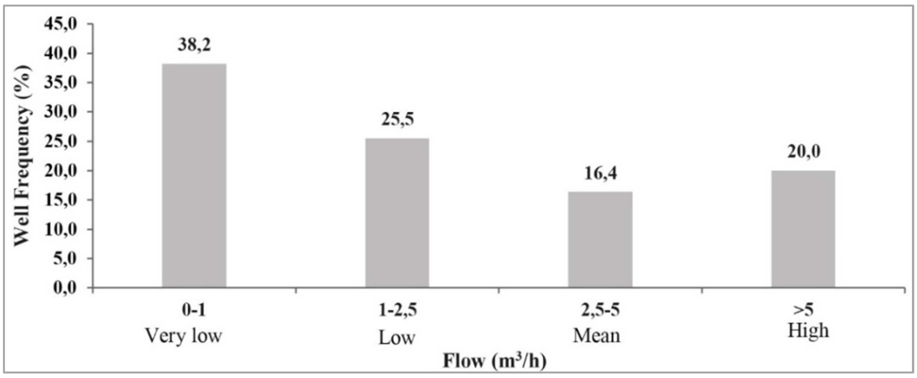

Figure 11. *Distribution of all well flow rates identified in the four classes defined by the CIEH (Interafrican Committee for Hydraulic Studies).*

5. Conclusion

Analysis of the peneplain portion coverage in the southwest Togo has allowed to highlight a dense lineament network in panafrican gneisso-migmatitic formations. Components of the network defined in all directions are clearly dominated, in number and weight, by the NE–SW (N30 - N60) lineaments. These lineament characteristics are identical to those of the fracture network on the geological map and in outcrop. The projection, on the lineament map, of all known wells in the sector, shows that the hydrogeological potential of the gneisso-migmatitic formations is mainly linked to the fracture network. In fact, the lineament- well coupling, shows that the most productive wells ($Q > 5\,m^3/h$) are associated with major fractures trending NE-SW. Of all the wells along the Keve - Amoussoukope road axis, more than one-third occur in the medium to high flow rate classes.

These preliminary results demonstrate the essential role of fracture network in the productivity of the aquifers in the panafrican basement in southwest Togo. Wider investigations that consider geophysical, hydro-geochemical data and the real menace from diverse sources (pesticides, herbicides, animal breeding …) will lead to a better quantitative and qualitative evaluation of the hydrogeological potential of all the gneisso-migmatitic formations in the South of Togo.

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