Spatial Dependency of Buruli Ulcer Disease on Geological Settings in Ghana

Saviour Mantey[1], Simon K. Y. Gawu[2], Richard K. Amankwah[3], Alfred Allan Duker[4]

[1]Department of Geomatic Engineering, University of Mines and Technology, Tarkwa, Ghana
[2]Department of Geological Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana
[3]Department of Mineral Engineering, University of Mines and Technology, Tarkwa, Ghana
[4]Department of Geomatic Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

Abstract: ***Tropical environments are known for their prevalence of a number of geochemical diseases. These are related to the very nature of their geological settings. Little research has, however, been conducted in geosciences in Ghana to investigate the link between geological settings and Buruli Ulcer (BU) disease. This research therefore examined the effect of geological settings on the spread of BU disease caused by Mycobacterium Ulcerans (MU) in the Upper Denkyira West District (UDWD), Amansie West District (AWD) with Tarkwa Nsuaem Municipality (TNM) as a case control study area. Geological maps of the study areas were extracted from the geological map of Ghana. Epidemiological data of BU disease collected from the National Buruli Ulcer Control Programme, district hospitals and from fieldwork were overlaid on geological maps of the study areas. Spatial analysis was then performed to identify the relationship between geological settings and BU disease spread in the study areas. Twenty-seven (27) communities were found to have cases of BU in the three study areas. Results also show that districts underlain by Birimian meta-sedimentary rock units which mainly contain minerals like of pyrites and arsenopyrites are more susceptible to BU disease than districts underlain by Tarkwaian siliciclastics and Birimian meta-volcanic rocks. This research thus offers an opportunity to link geological settings and BU disease as well as contributes to public health and environmental management in the study areas.***

Keywords: AWD, UDWD, TNM, Buruli Ulcer disease, Geological settings, Ghana

1. Introduction

Buruli Ulcer (BU), an emerging bacterial disease caused by *Mycobacterium Ulcerans (MU)*, is one of 17 recently classified neglected tropical diseases [1]. It mostly affects poor rural populations in tropical and sub-tropical countries, mostly in West Africa [2]. A landscape element such as geological settings may play important roles in the spread of BU disease. Evidence has shown that there is a link between geological settings and human health [3, 4]. Ghana has diverse geological settings characterized by a range of altitudes as well as a unique hydrological network.

Human health is often endangered as a result of environmental degradation through the disturbance of the natural geology. Interaction with the natural geology and environment is often harmless [4, 5]. However, for example, rural communities who are largely dependent on their local geology and environment for food and water could be exposed to geology-related diseases when large quantities of heavy and harmful metals are released into the environment [6]. Geological factors are known to play key roles in a range of environmental health issues, which ultimately impact the health of billions of people worldwide [4, 7]. People who depend very much on the land may be confronted with some health problems. Some communities may be exposed to impoverished soils (*e. g.*, Maputaland in South Africa) that could result in a number of diseases [8]. In other areas, there exists abundance of certain trace elements. The ingestion of such trace elements leads to high incidence of mineral toxicity, and consequently health hazards. An example is the arsenic poisoning of India and Bangladesh [8].

Rocks are also one of the leading sources of these elements. They are the fundamental source of all chemical or trace elements discovered on the earth naturally [7], some of which have adverse effect on health. For example, Fluoride often in high-grade metamorphic rocks in some communities has been the cause of dental fluorosis. However, where rocks in an area are also insufficient in essential minerals like iodine, mental retardation and brain damage occur in those areas [8].

Volcanoes have been noted as one of the main sources that bring all the toxicity from inside the earth to the outside [7]. They bring out trace metals such as arsenic, uranium, cadmium, beryllium, lead, mercury, radon, *etc.* For example, the explosive eruption of Mt. Lamington in Papua Guinea, which occurred in 1951 was followed by floods of the Sepik and Kumusi Rivers as well as mudflows that lasted until 1956 [9, 10]. *MU* infections were subsequently reported in 1957 mainly in settlements along the inundated portions of these rivers [11].

Reports also, indicate that there was a sudden increase of BU cases in Ghana with about 2000 cases recorded in the period 1993-1997 [12, 13]. The increase coincided with the legal registration of artisanal miners (1992-1996). Prior to the legal registration of artisanal miners, gold mining had increased significantly in the period 1980-1990 in the West African region [14, 15], thus disturbing the natural geology. Undeniably, the West African region experienced severe BU infections within the period 1980-1995 [14-18].

Usually mining and construction activities release large amounts of heavy metals such as arsenic, mercury and lead into nearby surface waters [19-21] as well as ground water sources [6, 22-24]. Due to the nature of gold ore and the method of mining, environmental degradation and metal pollution are dominant in such mining areas. Arsenic, for example, mobilizes in the environment as a result of arsenopyrite oxidation caused by mining activities as well as pH and Eh conditions [25, 26].

Analysis of water and soil samples from *galamsey* pits in communities of the Upper Denkyira West District (UDWD) and Tarkwa Nsuaem Municipality (TNM) by [27], revealed that concentrations of trace metals were consistently high in *galamsey* pits than in any other water body. The high trace metal concentrations suggest that these water bodies may harbor and promote the growth of the bacteria [27]. Rivers are a common drinking water source and arsenic in drinking water is known to suppress the immune system [28].

2. Regional Geology

The major rock units in Ghana fall within the Precambrian Guinean Shield of West Africa [29] and these are metamorphosed and folded in groups such as the Birimian, Tarkwaian, Dahomeyan Systems, the Togo Series and the Buem Formation [29]. The Precambrian rocks are overlain by late Proterozoic to Paleozoic rocks of the Voltaian System [29]. The Tertiary to Recent Sedimentary units are found along the coastal belt of the country, namely the Appollonian of the south-east (the Keta Basin), Accraian, Secondian and the Appollonian of the south-west (the Tano Basin). The Birimian Supergroup and the Tarkwaian System occur mainly in Western, Eastern, Ashanti, Central and the Northern, Upper West and Upper East Regions of Ghana whilst the Togo, Buem and Dahomeyan rock units occur in the Eastern and Volta Regions of the country [29] (Figure 1).

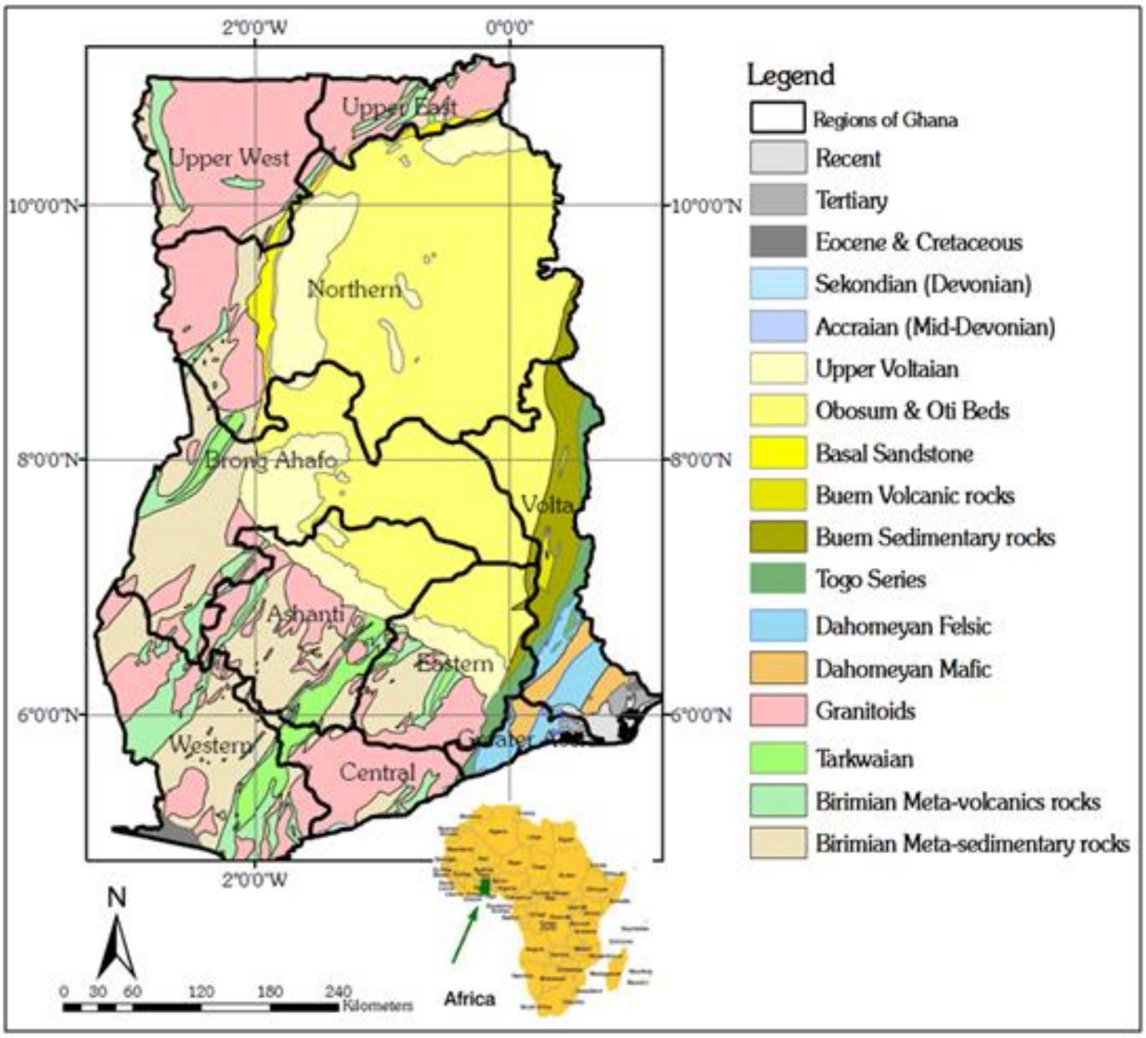

Figure 1: Geology of Ghana (source: Geological Survey Department, Accra, Ghana)

Emphasis would, however, be placed on the Birimian Supergroup and Tarkwaian System with associated basic intrusive sometimes referred to as undifferentiated granitoid since, Amansie West District (AWD), UDWD and TNM are represented by these major rock units.

3. The Birimian Supergroup

The Birimian Supergroup consists of a great thickness of isoclinally folded metamorphosed sediments intercalated with metamorphosed tuff and lava [30]. Large masses of granitoid bodies have also intruded the Birimian

Supergroup [31]. It is fissured to a larger extent compared to the Tarkwaian System. This supergroup is divided into upper and lower Birimian Series [29]. The meta-sedimentary rock units are predominant in the Lower series of the supergroup, whilst, the upper part of the supergroup is dominantly of meta-volcanic rock assemblage.

In the Birimian Supergroup, gold occurs in five parallel, more than 300 km long, northeast trending volcanic belts. They are segregated by basins holding pyroclastic and meta-sedimentary rock units [30]. They deeply penetrate fissures and shear zones in contact between meta-sedimentary and meta-volcanic rocks. The veins comprises: quartz with carbonate minerals, green sericite, carbonaceous partings and metallic sulphides of Fe, As, Zn, Au, Cu, Sb and Pb [31-33]. The Birimian Supergroup has a higher content of heavy metals than the Tarkwaian System [29, 31].

The Birimian Supergroup is mainly volcanic greenstones with intervening sedimentary rocks [29, 34]. They have granitoid intrusions with Birimian meta-sedimentary rock units particularly in places containing deposits composed of pyrite, arsenopyrite, chalcopyrite, galena, native gold and secondary hematite [34]. Meta-volcanic rocks are intruded by the Belt type granitoids. Meta-sedimentary rocks are intruded by the Basin type granitoid (s–type), thus, they are formed from sedimentary source [29].

4. The Tarkwaian System

The Tarkwaian System (TS) forms part of the West African Craton area which, is covered mostly by Birimian meta-volcanic and meta-sedimentary rocks [35]. The TS is the second oldest system in Ghana, and outcrops in a northeast-southwest trending belt in the Tarkwa area [35]. It stretches from near Axim in the Western region to the edge of the Voltaian Basin near Agogo in the Ashanti Akim District, a distance of about 250 km and a width of about 16 km. It also occurs at Bui in the Brong Ahafo Region [29]. The Tarkwaian is of shallow water continental origin derived from the Birimian and associated granitoids [29, 34]. The rocks consist of coarse, poorly sorted, immature sediments with low roundness, typical in part of a braided stream environment. The Tarkwaian sequence consists of clastic meta-sedimentary rocks which have suffered low grade regional metamorphism and alteration by hydrothermal solution [35]. It also consists of slightly metamorphosed, shallow-water and sedimentary strata. It is predominantly sandstone, quartzite, shale and conglomerate and is resting on and derived from the Birimian Supergroup [29]. Intrusive igneous rocks contribute to about 20% of the total thickness of the TS in the Tarkwa area. These range from hypabyssal felsic to mafic igneous rocks [36]. Dixcove-type Granitoids has also intruded the Tarkwaian System in many places [29]. Non-sulphidic paleoplacer ore occurs mainly in hard rock. It is particularly associated with Banket conglomerates of the Tarkwaian [29, 35]. The TS is subdivided into four stratigraphic units as summarized in Table 1.

Table 1: The Lithologic Composition of the Tarkwaian System (Source: Junner, Hirst and Service, 1942)

Series/Formation	Lithologic Composition
Huni sandstone and Dompim phyllites	Sandstones, quartzites, grits and quartzites with bands of phyllites
Tarkwa phyllite	Phyllites, chlorites, sericites and schist transitional to Huni sandstone
Banket Series	Sandstones, quartzite, grits and conglomerates (quartz pebble conglomerates and breccia conglomerates)
Kawere Series	Quartzites, Grits, phyllites and conglomerates

4. 1 Characteristics of the Tarkwaian System

The Tarkwaian System is characterized by Huni sandstone and Dompim phyllites, Tarkwa phyllite, Banket Series and the Kawere Series.

The Huni sandstone is the weathered form of feldspathic quartzites which are generally finer grained than the quartzites in the Banket Series [29]. It comprises, sandstones, grits and quartzites with bands of phyllites and may be cross bedded [29, 35].

The Tarkwa phyllite is a fine grained meta-siltstones and meta-mudstones. They are divided into those with or without chloritoid. It unconformably overlies the Banket [29, 35]. The Banket Series is composed mainly of quartzite, grit and conglomerates [29, 34]. Four reefs or conglomerate bands and their stratigraphical relationships in the area were named by [35]. They are: Breccia reef, Middle reef, Basal or main reef (richest in gold) and Sub-basal reef. The pebbles in the conglomerates are mainly from vein-quartz with the remaining from Birimian schists. The matrix consists principally of quartz and sands (mainly hematite and minor ilmenite, magnetite and rutile). Other minor constituents are sericites, chlorites, chloritoids, tourmaline, zircon, garnet and gold. The Kawere group consists of quartzites, grits, breccias and conglomerates with the most conspicuous members of the group being the conglomerates with interbedded grits and quartzites. The conglomerates normally consist predominantly of pebbles of very fine-grained silicified Birimian greenstones and hornstone in a matrix of quartz, feldspar, chlorite, carbonate, epidote and magnetite. The Kawere is poorly sorted, matrix supported and cross bedded. The quartzites and grits are normally greenish-grey in colour and are poorly bedded and contain no economic gold mineralization [29, 35].

4. 2 Similarities between Tarkwaian and Birimian Supergroup

Although lithologically, the Tarkwaian and Birimian are different, there exist some similarities between them. The Birimian Supergroup and Tarkwaian are intruded by three types of granitoids. The three different granitoid suites present in Ghana are referred to as the Dixcove, Cape

Coast and Bongo granitoids [37]. The following distinguishing characteristics of the different granitoids have been explained by [34, 37] as follows:

Dixcove-Type Granitoids: They are small, unfoliated plutonic bodies that intrude Birimian belt volcanics. This suite is made up of quartz diorite, tonalite and trondhjemite, granodiorite, adamellite and to a lesser degree, granite.

Cape Coast-Type Granitoids: They are classified as large, syntectonic, foliated granitoid batholiths that typically intrude the Birimian meta-sedimentary strata. Typical lithologies include: quartz diorites, tonalities and trondhjemites, granodiorites, adamellites and granites. They are known to have metamorphic aurelos with mineral assemblages that show pressure of at least 4kb and temperatures around 500 °C.

Bongo-Type Granitoids: These bodies intrude Tarkwaian sediments in the Bole-Navrongo belt. Moreover, they are post-tectonic in origin and are petrographically characterized by pink phenocrysts of alkali feldspar. Apart from their different lithologic compositions, the main difference between the Tarkwaian and Birimian was ascertained. The two systems both have granitoid intrusions but the Birimian meta-sedimentary rocks have their granitoid intrusions in places containing deposits of pyrites, arsenopyrites minor chalcopyrite, sphalerite, galena, secondary hematite and native gold [29]. Both the Birimian Supergroup and the Tarkwaian, exhibit northeast-southwest strike and also have the same level of metamorphism (greenschist facies).

5. Materials and Methods

5. 1 Study Areas

The study areas are: AWD, UDWD and TNM. These study areas were selected due to their similarities in socio-economic activities (*e. g.* illegal "*galamsey*" mining and farming activities) and BU prevalence. The AWD lies between latitudes 6°07' N and 6°35' N and longitudes 1°42' W and 2°08' W (Figure 2). The district is bounded by UDWD, Amansie Central District, Bibiani-Anwiaso-Bekwai District, Atwima Mponua District, Atwima Nwabiagya District, Atwima Kwanwoma District and Bekwai Municipal. The District is a tropical rain forest area of about 1 320 km^2 with an estimated population of 134 331 (2010 Population and Housing Census). It is approximately 60 km southwest of Kumasi, the regional capital of Ashanti. AWD has the highest BU prevalence rate of 150. 8 per 100 000 in the country [14, 15, 38] and the second highest reported active cases across the country [38]. The main occupation of the people is subsistence farming and small scale "*galamsey*" mining. The AWD is drained by the Offin and Oda rivers and their tributaries (Figure 2).

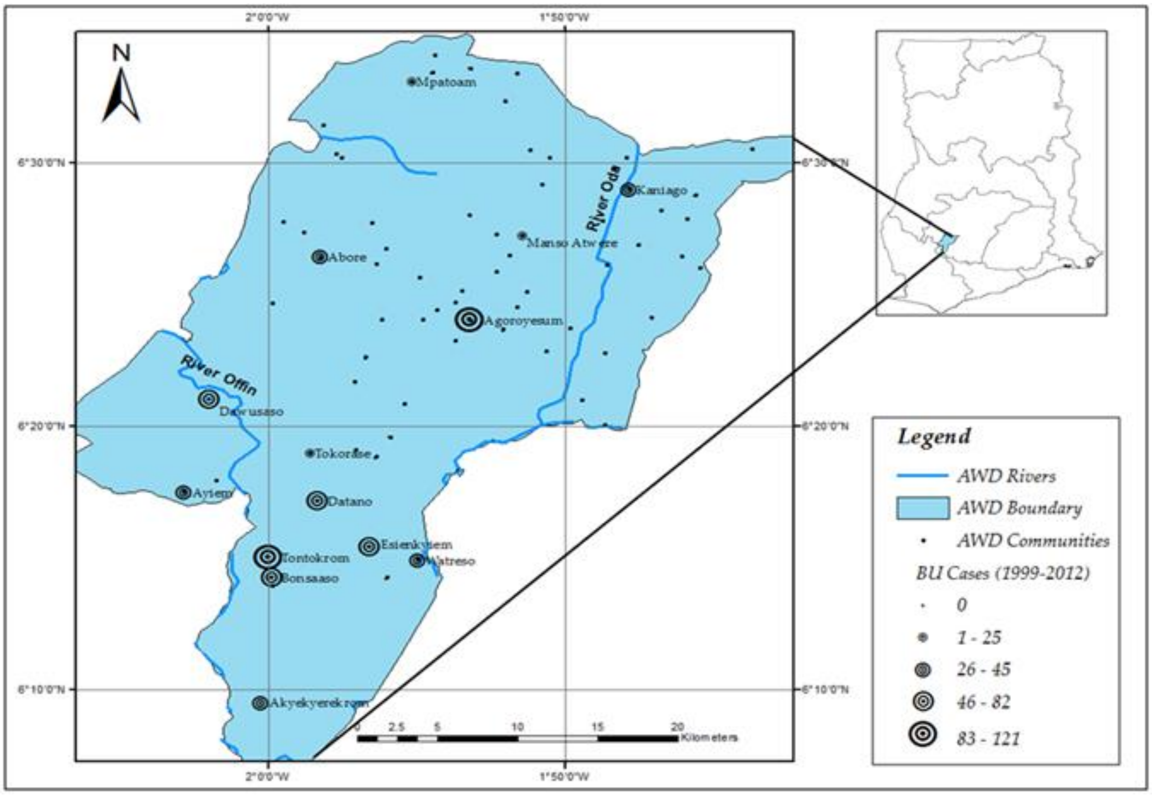

Figure 2: Map of Amansie West District

UDWD is the second study area and lies between latitudes 5° 54' N and 6° 18' N and longitudes 1° 49' W and 2° 12' W of the Greenwich Meridian (Figure 3). The District is bounded to the south-east by Upper Denkyira East District, Amansie Central District and Obuasi Municipality. Bounded to the south-west are Wassa Amenfi East and Amansie West Districts. The District is also bounded to the north-west by Bibiani-Anwiaso-Bekwai and Wassa Amenfi West Districts. UDWD covers an area of about 1 700 km^2 with an estimated population of about 132 864

(2010 Population and Housing Census). While the Central Region has the highest overall prevalence rate of active cases [38], UDWD is among the most endemic districts in the Region and has the third highest prevalence rate of 114.7 per 100 000 nationwide together with Upper Denkyira East District after Asante Akim North District (prevalence rate of 131. 5 per 100 000) and Amansie West District (prevalence rate of 150. 8 per 100 000) [38]. Subsistence farming and small scale "*galamsey*" mining are the main occupation of the people in the District. UDWD is drained by Offin, Dia and Subin rivers as well as their tributaries (Figure 3).

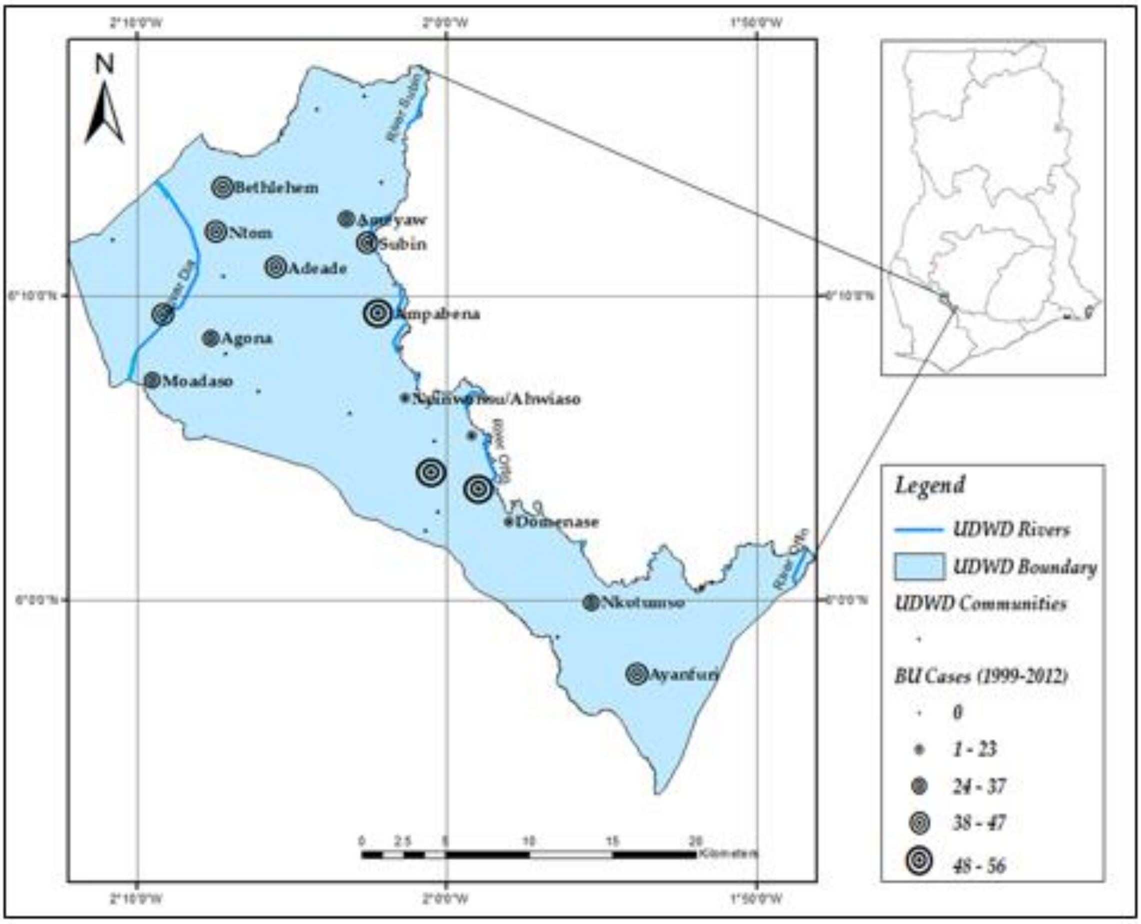

Figure 3: Map of Upper Denkyira West District

The third study area; TNM occupies the mid-southern part of the Western Region of Ghana with Tarkwa as its administrative capital. The TNM is geographically located between latitudes 4°53' N and 5°23' N and longitudes 1°47' W and 2°14' W (Figure 4). The Municipality is bounded to the north by Prestea-Huni Valley District, to the south by Ahanta West District, to the West by Nzema East Municipality and to the East by Mpohor Wassa East District.

The Municipality has a total land area of 1 208. 7 km^2 with a population of approximately 90 477 (2010 Population and Housing Census). Subsistence farming is the major occupation of the people although "*galamsey*" mining is also practiced. Large-scale mining is the main industrial activity in the TNM [22]. There is only one community (Kedadwen), with reported cases of BU disease in the Municipality. The Municipality is drained by Bonsa and Ankobra rivers as well as their tributaries (Figure 4).

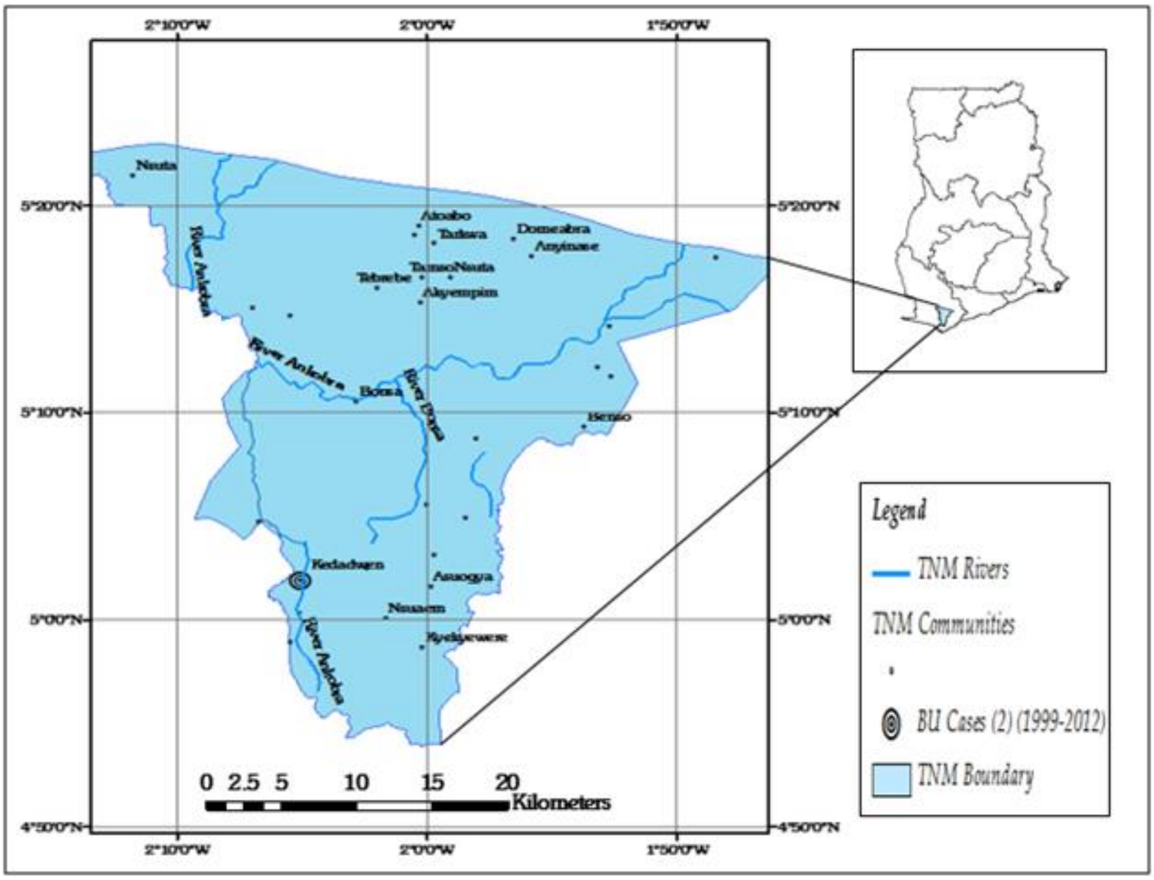

Figure 4: Map of Tarkwa Nsuaem Municipality

5. 2 Materials

Data for the study include: Geological map of Ghana, District map of Ghana (in shapefile format) and Epidemiological data of BU for AWD, UDWD and TNM. The Epidemiological data was obtained from the National Buruli Ulcer Control Programme and from field investigation based on clinical case definition of WHO [17, 39]. The Geological Map of Ghana was obtained from the Geological Survey Department.

5. 3 Method

The Geological map of Ghana was orthorectified to the Universal Transverse Mercator projection zone 30 North (UTM 30 N). Geological maps of the study areas were used to delineate BU disease prone communities by the method of point-in-polygon topological overlay. The point-in-polygon topological overlay method was used to determine the spatial coincidence of BU endemic communities within the study areas and their geological settings. A BU-Geology Delineator (BGD) based on the point-in-polygon topology overlay was developed in a C-Sharp programming language. The well-defined orthorectified geological map and district map of Ghana was uploaded unto the BGD. The communities with known X, Y coordinates were also uploaded unto the BGD. The BGD extracts the geology type and district(s) within the communities unto a table. The BU endemic communities were then assigned the geological types and the districts within which they coincide (Table 2). The district boundaries of the BU endemic communities were also automatically extracted using the BGD (Figure 5).

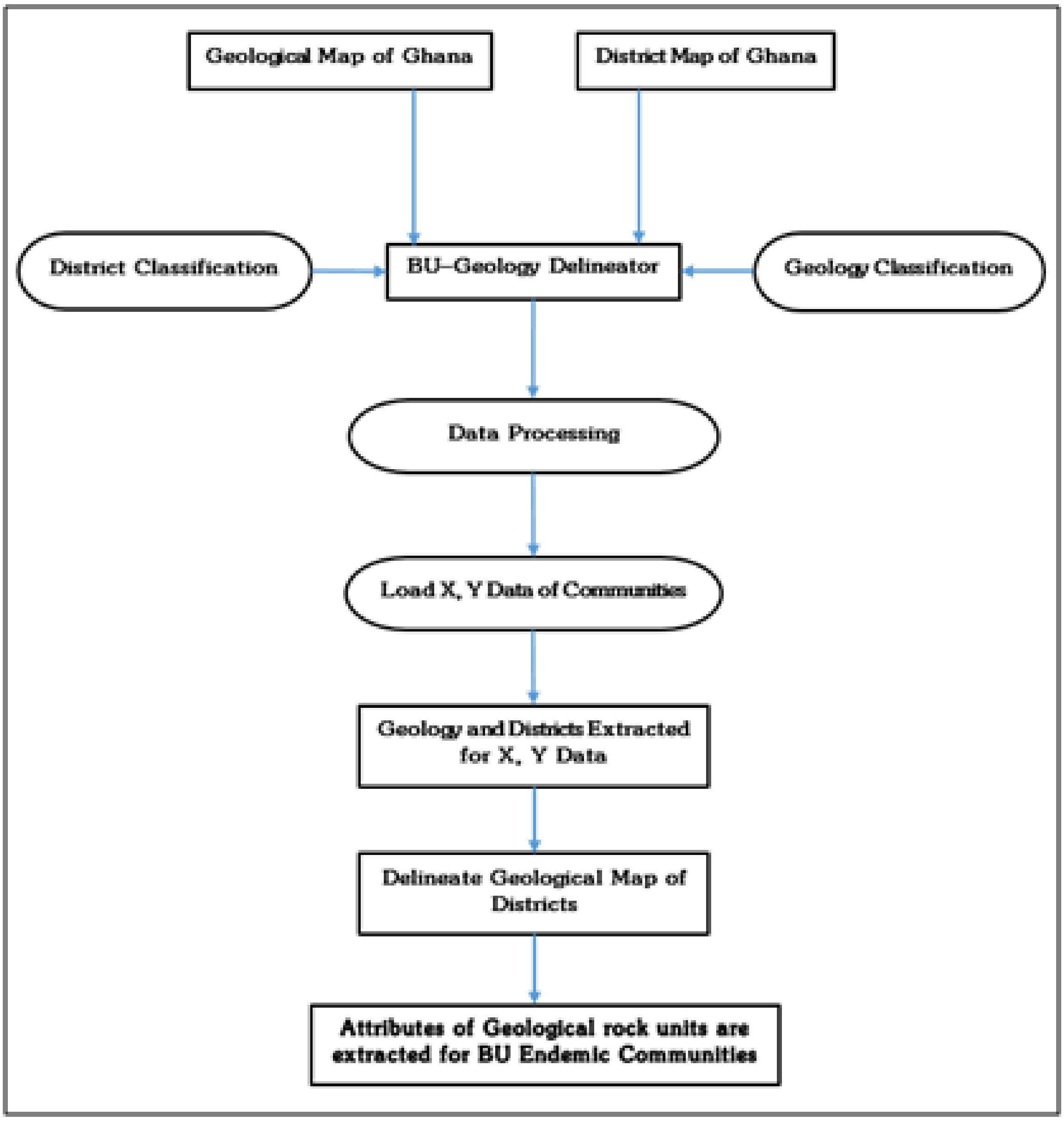

Figure 5: Flow Chart of Methods

6. Results

This research observed that the geology of AWD and UDWD are mainly Birimian meta-sedimentary rock units (Figure 6 and 7; Table 2). Performing point-in-polygon topological overlay of the communities on the geological map showed that most of the BU communities fell in the Birimian meta-sedimentary rock units (Figure 6 and 7). The Birimian meta-sedimentary rock units are largely composed of gold-bearing quartz veins containing carbonate minerals as well as metallic sulfides. The geology of TNM also consists mainly of Tarkwaian and Birimian meta-volcanic rocks as well as some basic intrusive (Figure 8).

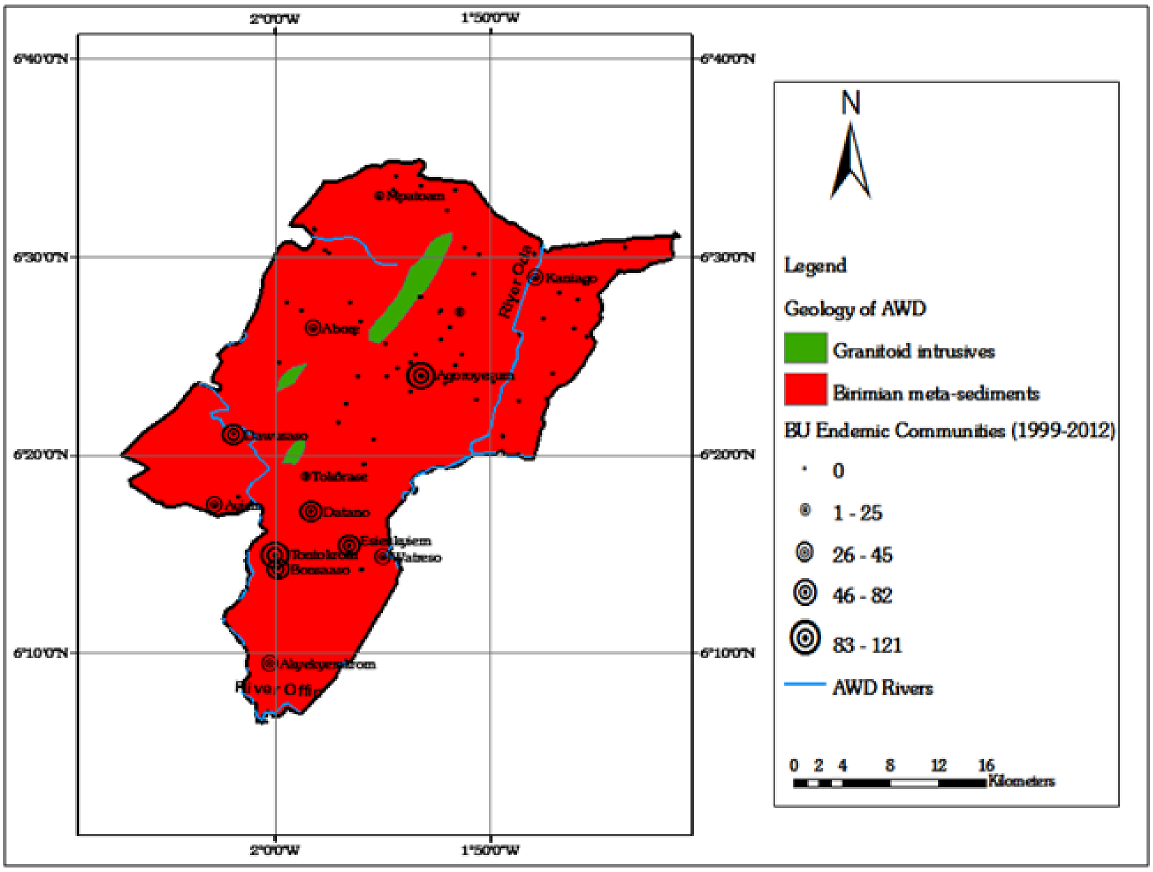

Figure 6: Geological Map of AWD

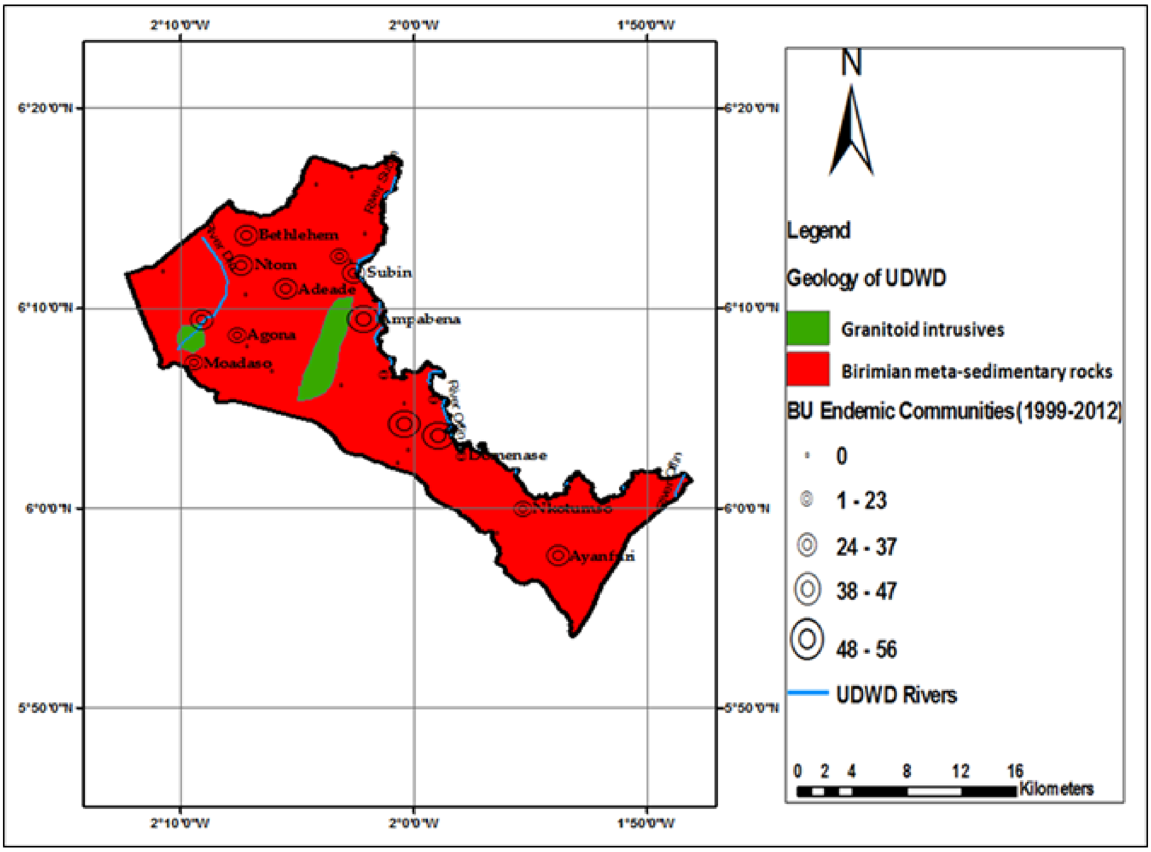

Figure 7: Geological Map of UDWD

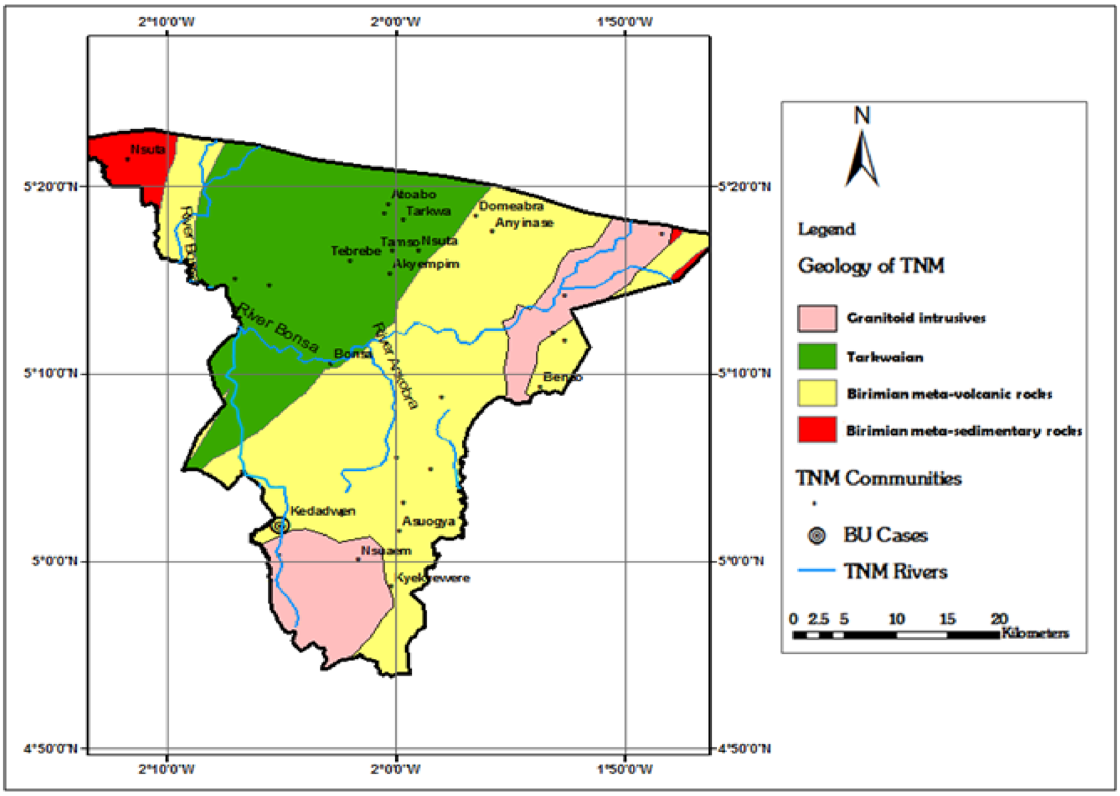

Figure 8: Geological Map of TNM

Table 2: Attributes of BU-Geology Delineator

No.	Community Name	No. of BU Cases	Geology Type	District/Municipality
1.	Dawusaso	62	Birimian meta-sedimentary rocks	AWD
2.	Abore	62	Birimian meta-sedimentary rocks	AWD
3.	Ayiem	35	Birimian meta-sedimentary rocks	AWD
4.	Tontokrom	121	Birimian meta-sedimentary rocks	AWD
5.	Bonsaaso	82	Birimian meta-sedimentary rocks	AWD
6.	Akyekyewere	43	Birimian meta-sedimentary rocks	AWD
7.	Watreso	45	Birimian meta-sedimentary rocks	AWD
8.	Essienkyiem	55	Birimian meta-sedimentary rocks	AWD
9.	Agoroyesum	120	Birimian meta-sedimentary rocks	AWD
10.	Datano	76	Birimian meta-sedimentary rocks	AWD
11.	Diaso	47	Birimian meta-sedimentary rocks	UDWD
12.	Moadaso	30	Birimian meta-sedimentary rocks	UDWD
13.	Agona	35	Birimian meta-sedimentary rocks	UDWD
14.	Ntom	41	Birimian meta-sedimentary rocks	UDWD
15.	Adeade	47	Birimian meta-sedimentary rocks	UDWD
16.	Subin	42	Birimian meta-sedimentary rocks	UDWD
17.	Ameyaw	37	Birimian meta-sedimentary rocks	UDWD
18.	Ampabena	55	Birimian meta-sedimentary rocks	UDWD
19.	Nyinwonsu	22	Birimian meta-sedimentary rocks	UDWD
20.	Domenase	22	Birimian meta-sedimentary rocks	UDWD
21.	Ayanfuri	43	Birimian meta-sedimentary rocks	UDWD
22.	Nkotumso	30	Birimian meta-sedimentary rocks	UDWD
23.	Abora	56	Birimian meta-sedimentary rocks	UDWD
24.	Treposo	56	Birimian meta-sedimentary rocks	UDWD
25.	Adaboa	23	Birimian meta-sedimentary rocks	UDWD
26.	Bethlehem	45	Birimian meta-sedimentary rocks	UDWD
27.	Kedadwen	2	Birimian meta-volcanic rocks	TNM

7. Discussion

The aim of this research was to determine the relationship between BU disease and geological setting of AWD, UDWD and TNM. It has become an enigma understanding the high prevalence of BU disease in AWD and UDWD compared to TNM since most activities like farming, mining and "*galamsey*" operations take place in all the study areas. However, a thorough study of the geologies of AWD and UDWD shows that they are dominated by Birimian meta-sedimentary rocks as compared to TNM. The Birimian meta-sedimentary rock constitutes gold-bearing quartz veins with high concentrations of arsenic, cadmium, copper, iron, lead and zinc.

Arsenic can be found in arsenopyrite, (FeAsS) where the latter occurs as an important component of gold-bearing quartz veins [19] and is generally intergrown with pyrite and minor amounts of sulphides namely, sphalerite, galena, chalcopyrite and stibinite. Arsenic is a metalloid, toxic in the environment [40]. The most common natural occurrences of arsenic are associated with gold deposits and further exposed by activities like mining (especially, "*galamsey*" operations). A research discovered that arsenic-rich discharges are well known from gold mine tailings and are released during weathering and ground water interactions with arsenic-rich rocks [6]. Arsenic forms a compound with oxygen and thus makes it mobile in both reducing and oxidizing environments.

Mine tailings, which generally contain arsenic are washed into rivers and drainages during surface runoff and erosion. This causes the arsenic to be released into rivers and stream channels. [38], also, found out that 52 out of 90 BU patients used surface water as a source of drinking water. This clearly emphasizes the high prevalence of BU disease where people have access to water supplies from surface waters, and the possible role of arsenic in BU disease.

Interestingly, farmers in these districts tend to farm in the soil-rich floodplains of rivers and streams during the dry season, where they also irrigate the food-crops. Soils in floodplains have high cation exchange capacity and able to cause increased concentration of arsenic in the soils of the floodplains. Food-crops in these areas take up arsenic [41, 42].

According to [43], individuals with high level of arsenic in their bodies have impaired immune response; and immuno-compromised persons are susceptible to the BU disease [44, 45]. Ingestion therefore of arsenic-enriched surface waters and food-crops irrigated with such waters could impact adversely on the immunity of the people and predispose such persons to BU disease.

Arsenic is also able to accumulate in the fatty tissues of the skin [46] because it has high lipid solubility, which may provide optimum and favorable conditions for the microorganisms to grow [47], and it is interesting to note that BU disease is primarily an infection of the subcutaneous fat where myriads of the mycobacteria in their spherule forms remain. Arsenic could possibly be related to the high prevalence of BU disease in AWD and UDWD as compared to TNM. For example, [48] found as much as 2900 $\mu g l^{-1}$ of arsenic in surface waters in AWD.

Furthermore, though the geological settings might be related to the cause of BU disease, human activities (like farming, mining, deforestation, *etc.*) might exacerbate the growth and transmission of the disease.

8. Conclusions

The results show that the geology of TNM is broadly Tarkwaian and to a lesser extent Birimian meta-volcanic rocks. The geology of AWD and UDWD is made up of mainly Birimian meta-sedimentary rocks and some intrusive.

Most of the BU endemic communities were found in the Birimian meta-sedimentary rock units which consist of pyrites, arsenopyrite, chalcopyrite, sphalerite, galena and secondary hematite.

The Birimian meta-sedimentary rock is linked with arsenic and may contaminate rivers and streams that serve as sources of drinking water for the inhabitants. Food-crops may take up arsenic where these contaminated waters are used to irrigate them.

Arsenic is known to be toxic and suppresses the immune system which might enhance BU disease infections. It is also known that immuno-compromised persons are susceptible to the BU disease. Communities which depend on arsenic-enriched waters may have their immune system compromised and therefore susceptible to BU disease. Variations in geology of AWD, UDWD and TNM could possibly be linked to the difference in prevalence of BU disease. Therefore, geological settings could possibly have a relationship with BU disease.

Acknowledgements

This research is part of a larger project funded by the National Science Foundation (CNH Award #0909447: Research and Education on Buruli ulcer, Inundations, and Land Disturbance - ReBUild, rebuildghana. org) involving geographers, earth scientists, medical professionals, and education specialists from several US and Ghanaian universities and other research partners. The authors will like to express their profound gratitude to Mr R. S. Nartey, a Geologist, whose expertise and knowledge of the study areas contributed to the success of this research.

References

[1] Anon., (2008), "World Health Organization, Buruli ulcer progress report, 2004-2008", Weekly Epidemiological Records, Vol. 83, pp. 145-54.

[2] Wagner, T., Benbow, M. E., Burns, M., Johnson, R. C., Merritt, R. W. , Pamela, J. Qi and Small, L. C. (2008), "A Landscape-based model for predicting Mycobacterium ulcerans infection (Buruli Ulcer disease) presence in Benin, West Africa", *Ecohealth*, Vol. 5, No. 1, pp. 69-79.

[3] Davies, T. C. (2008), Environmental health impacts of East African Rift volcanism. *Environmental Geochemistry and Health*, Vol. 30, Section 4, pp. 325–338.

[4] Finkelman, R. B., Skinner, H. C. W, Plumlee, G. S. and Bunnell, J. E., (2001), Medical Geology, Geotimes, November.

[5] Davies, T. C. (1996), Geomedicine in Kenya, *Journal of African Earth Sciences*, Vol. 23, Issue 4, pp. 577–591.

[6] Smedley, P. l. and Kinniburgh, D. G. (2002), "A review of the source, behaviour and distribution of arsenic in natural waters", *Applied Geochemstry*, Vol. 17, pp. 517-568.

[7] Olle, S. (2007), Medical Geology: An opportunity for the future. AMBIO: *A journal of human Environment*, Vol. 36, Issue 1, pp. 114-116.
[8] Dissanayake, C. (2005), Of stones and health: Medical Geology in Sri Lanka, *Science* Vol. 309, pp. 883-885.
[9] Simkin, T. and Siebert, L. (1994), Volcanoes of the world: Geoscience Press, Tucson, Arizona, 349 pp.
[10] Taylor, G. A. M. (1957), "The 1951 eruption of Mount Lamington, Papua: Commonwealth of Australia, Bureau of Mineral Resources", *Geology and Geophysics Bulletin*, No. 38, 117 pp.
[11] Radford, A. J. (1974), "*Mycobacterium ulcerans* infection in Papua New Guinea", *Papua New Guinea Medical Journal*, Vol. 17, pp. 145-149.
[12] Grosset, J., Kanga, J. -M., Portaels, F., Guédénon, A., Tignokpa, N., Scherpbier, R., Asiedu, K. (2000), Country assessment reports (Annex 5). In: Asiedu, K., Scherpbier, R., Raviglione, M., (eds.), *BURULI ULCER: Mycobacterium ulcerans infection*, World Health Organisation, Global Buruli Initiative, pp. 87-92.
[13] Portaels, F. (1998), Historical overview of Buruli ulcer. International Conference on Buruli ulcer Control and Research, Yamoussokro, Côte d'Ivoire, 6-8 July.
[14] Amofah, G. K. (1995), Control and management of Buruli ulcer disease, *Ghana Medical Journal, Vol.* 29, pp. 589-602.
[15] Amofah, G. K., Sagoe-Moses, C., Adjei-Acquah, C., Frimpong, E. H. (1993), Epidemiology of Buruli ulcer in Amansie West District, Ghana. *Transaction of the Royal Society of Tropical Medicine and Hygiene, Vol.* 87, pp. 644-645.
[16] Aguiar, J. and Stenou, C. (1997), Buruli ulcers in rural areas of Benin: management of 635 cases, *Med Trop* (Mars*)*. Vol. 57, pp. 83-90.
[17] Marston, B. J., Diallo, M. O., Horsburgh, R. C., Diomande, I., Saki, M. Z. , Kanga, M. , Patrice, G., Lipman, H. B. , Ostroff, S. M. , Good, R. C. (1995), Emergence of Buruli ulcer disease in Daloa region of Côte d'Ivoire, *American Journal of Tropical Medicine and Hygiene, Vol.* 52, pp. 219-224.
[18] Monson, M. H., Gibson, D. W., Connor, D. H., Kappes, R., Hienz, H. A. (1984), *Mycobacterium ulcerans* in Liberia: a clinicopathologic study of 6 patients with Buruli ulcer, Acta *Trop* Vol. 41, pp. 165-172.
[19] Smedley, P. L. , Edmunds, W. M. , Pelig-Ba, K. B. (1996), Mobility of arsenic in ground water in the Obuasi gold-mining area of Ghana: some implications for human health. In: Appleton, J. D., Fuge, R., McCall, G. J. H. (eds.), *Environmental Geochemistry and Health*, Geological Society Special Publication No. 113, pp. 163-181.
[20] Williams, M., Fordyce, F., Paijitprapapon, A., Charoenchaisri, P. (1996), Arsenic contamination in surface drainage and groundwater in part of the southeastern Asian tin belt, Nakhon Si Thammarat Province, southern Thailand, *Environmental Geology*, Vol. 27, pp. 16-33.
[21] Azcue J. M., Murdoch, A., Rosa, F., and Hall, G. E. M. (1994), Effects of abandoned goldmine tailings on the arsenic concentrations in water and sediments of Jack of Clubs Lake, BC. *Environmental Technology*, Vol. 15, pp. 669-678.
[22] Avotri, T. S. M., Amegbey, N. A., Sandow, M. A. and Forson, S. A. K. (2002), The health impact of cyanide spillage at gold fields Ghana Ltd., Tarkwa. May (funded by Goldfields Ghana limited, GFGL*)*
[23] Armienta, M. A., Rodriguez, R., Aguayo, A., Ceniceros, N., Villasenor, G., and Cruz, O. (1997), Arsenic contamination of groundwater at Zimapan, Mexico. *Hydrogeology Journal, Vol.* 5, pp. 39-46.
[24] Del Razo, L. M., Arellano, M. A., Cebrián, M. E. (1990), The oxidation states of arsenicin well-water from a chronic arsenicism area of northern Mexico, *Environmental Pollution, Vol.* 64, pp. 143-153.
[25] Griffis, R. J., Barning, K., Agezo, F. L. and Akosah, F. K. (2002), Gold deposits of Ghana, Minerals Commission of Ghana, Accra.
[26] Osae, S., Kase, K. and Yamamoto, M., (1995). "A geochemical study of the Ashanti gold deposit at Obuasi, Ghana. Okayama University", Earth Science Report, Vol. 2, pp. 81-90.
[27] Hagarty, J. (2012), Spatial Variation of Chemical Constituents in Natural Waters and their Relation to Incidence of Buruli Ulcer in Gold-Mining Regions of Ghana, The Pennsylvania State University, Unpublished MSc Thesis, 92 pp.
[28] Banerjee, N; Banerjee, S., Sen, R., Bandyopadhyay, A., Sarma, N., Majumder, P., Das, J. K., Chatterjee, M., Kabir, S. N., and Giri, A. K. (2009), "Chronic arsenic exposure impairs macrophage functions in the exposed individuals" *Journal of Clinical Immunology*, Vol. 29, pp. 582-594.
[29] Kesse, G. O. (1985), The mineral and rock resources of Ghana. A. A. Balkema, Rotterdam, 610 pp.
[30] Attoh, K. (1980), Structure, stratigraphy and some chemical characteristics of an early Proterozoic (Birimian) volcanic belt, northeastern Ghana, in Current Research, Part C, Geological Survey of Canada, Paper 80-1c, pp. 69-80.
[31] Dzigbodi-Adjimah, K. (1993), "Geology and geochemical patterns of the Birimian gold deposits, Ghana, West Africa." *Journal of Geochemical Exploration*, Vol. 47, pp. 305-320.
[32] Bowell, R. J. (1992), "Supergene gold mineralogy at Ashanti, Ghana: implications for the supergene behaviour of gold", *Mineralogical Magazine, Vol.* 56, pp. 545-560.
[33] Wright, J. B., Hastings, D. A., Jones, W. B., (eds.), (1985), *Geology and Mineral Resources of West Africa*, George Allen and Unwin Publishers, London, 185 pp.
[34] Leube, A., Hirdes, W., Mauer, R. and Kesse, G. O. (1990), "The Early Proterozoic Birimian Supergroup of Ghana and Some Aspects of Its Associated Gold Mineralisation", *Precambrian Research*, Vol. 46, No. 1-2, pp. 139-165.
[35] Junner, N. R. Hirst T. and Service, H. (1942), "The Tarkwa Goldfield", Gold Coast Geological Survey Memoir, Vol. 6, pp. 48-55.

[36] Kuma, J. S., (2004), "Is Groundwater in the Tarkwa Gold Mining District of Ghana Potable?" *Environmental Geology*, Vol. 45, No. 3, pp. 391-400.
[37] Eisenlohr, B. N. and Hirdes, W. (1992), "The Structural Development of the Early Proterozoic Birimian and Tarkwaian Rocks in Southwest Ghana, West Africa", *Journal of African Earth Sciences*, Vol. 14, No. 3, pp. 313-325.
[38] Amofah, G. K., Bonsu, F., Tetteh, C., Okrah, J., Asamoa, K., Asiedu, K., Addy, J. (2002), Buruli ulcer in Ghana: Results of a national case search. *CDC: Emerging Infect Dis* vol. 8, no. 2. Http://www. cdc. gov/ncidod/eid/vol8no2/01-0119. htm. Accessed (8/08/2014).
[39] Asiedu, K., Meyers, W., Agbenorku, P. (2000), Clinical features and treatment. In: Asiedu, K., Scherpbier, R., Raviglione, M. (eds). BURULI ULCER: Mycobacterium ulcerans infection, World Health Organisation, Global Buruli Initiative, pp. 37-38.
[40] Adriano, D. (1986), Trace elements in the terrestrial environment. New York: Springer Verlag. 533 pp.
[41] Alam, M. G. M., Snow, E. T. and Takana, A. (2003), "Arsenic and heavy metal contamination of vegetables grown in Samta village, Bangladesh", *Science of the Total Environment*, Vol. 308, pp. 83-96.
[42] Warren, G. P., Alloway, B. J., Lepp, N. W., Singh, B., Bochereau, F. J. M. and Penny, C. (2003), "Field trials to assess the uptake of arsenic by vegetables from contaminated soils and soil remediation with iron oxides", *Science of the Total Environment*, Vol. 311, pp. 19-33.
[43] Gonseblatt, M. E., Vega, L., Montero, R., Garcia-Vargas, G., Del Razo, L. M. , Albores, A., Cebrian, M. E. , Ostrosky-Wegman, P. (1994), "Lymphocyte replicating ability in individuals exposed to arsenic via drinking water", *Mutation Research*, Vol. 313, pp. 293-299.
[44] Stienstra, Y., van der Graaf, W. T. A., teMeerman, G. J., The. T. H., de Leij, L. F., van der Werf, T. S. (2001), Susceptibility to development of Mycobacterium ulcerans disease: review of possible risk factors, *Tropical Medicine and International Health*, Vol. 6, No. 7, pp. 554-562.
[45] van der Werf, T. S., van der Graaf, T. A., Tappero, J. W., Asiedu, K. (1999), Mycobacterium ulcerans infection, *The Lancet*, Vol. 354, pp. 1013-1018.
[46] Isensee, A. R., Kearney, P. C., Woolson, E. A. , Jones, G. E. , Williams, V. P. (1973), Distribution of alkyl arsenicals in model ecosystem, *Environmental Science and Technology, Vol.* 7, pp. 841-845.
[47] Ahmann, D., Roberts, A. L., Krumholz, L. R., Morel, F. M. (1994), Microbe grows by reducing arsenic, *Nature*, Vol. 371, 750 pp.
[48] Duker, A. A., Carranza, E. J. M., Hale, M. 2005. Spatial relationship between arsenic in drinking water and *Mycobacterium ulcerans* infection in the Amansie West District. *Mineralogical Magazine*, Vol. 69, pp. 707-717.

Author Profile

Saviour Mantey is a lecturer at the University of Mines and Technology (UMaT), Tarkwa, Ghana. He obtained his MPhil degree in GIS and Remote Sensing from the University of Cambridge, UK. His research interest includes application of Remote Sensing and GIS in Health and Environmental Analysis, Web GIS Applications using Open Source Software. This publication is part of his PhD Thesis titled "Identification of Landscape Elements implicated in Buruli Ulcer Endemic Regions of Ghana: the GIS and Remote Sensing approach".

Dr. Simon K. Y. Gawu holds PhD in Civil and Environmental Engineering from the University of Witwatersrand, South Africa. He is a Senior Research Fellow in the Geological Engineering Department of the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. His research areas include, among others; Characterization and Stabilization of Mine Waste and its environmental impacts, Environmental Issues regarding Small-Scale Mining Activities, Alluvial Gold Exploration and its implication for evaluation, Lithomargic Clays Origin and Characterization for Industrial use, Geochemical Characterization of Bauxite Deposits for their Genesis, Blending and Treatment.

Prof Richard Kwasi Amankwah graduated with a PhD in Biohydrometallurgy from Queen's University. He is a professor at the University of Mines and Technology and the Chief Executive Officer of Process Innovations (mineral and architectural consulting firm in Ghana). He is an international scholar with several publications in the field of mineral engineering.

Prof Alfred Allan Duker graduated with a PhD from ITC, Netherlands. He is a professor at the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana. He is an international scholar with a number of publications in his field of study.