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Geology, Palaeodeposition and the Involvement of Rhyolite Melts in the Petrogenesis of the Tabenken Coal Seam in the North West Region of Cameroon

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Abstract

The discovery of patches of a coal deposit and other associated sedimentary and volcanic rocks in Tabenken North West Cameroon has raised the question of the geology and palaeoenvironment of that area. This Region, which is predominantly characterized by a granitoid basement of Precambrian age is in most parts overlain by Cenozoic basalts, hawaite, mugearite, trachyte and rhyolites. Volcanic outpours modified the geomorphology of the area into a series of hills and valleys. We investigated the geological setting in view of reconstituting the palaeodepositional environment of the Tabenken Coal Seam. Field studies show that the coal occurs in form of inclusions within sandstones, high grade coal bed, massive beds exposed by landslides and in alkali rhyolites. The results of Ultimate analyses of the coal indicate bituminous coal with 58% Carbon, sulfur content as low as 0.12% and ash content of 17%. The occurrence of a well stratified dark volcanic ash bed in the area is interpreted to be an interactive product of the explosive volcanic activity and weathering. Field examination of the area suggests that it was a micro-continental sedimentary palaeo-basin which was later infilled with Cenozoic volcanic outpours which probably modified the chemistry of the coal to meta-anthracites. The actual ages of the coal as well as the associated sedimentary units have not been established, meanwhile, the volcanism started some 31 ma ago.

Keywords

Tabenken, Palaeodepositional Environment, Bituminous Coal, Anthracite, Meta-Anthracite

1. Introduction

In Cameroon there are two major groups of sedimentary basins: coastal and inland. The coastal basins comprise the Kribi/Campo, Douala and Rio Del Rey (Ngeuetchoua, 1996; Angoua, 2006; Ngos & Mbesse, 2006; Njoh, 2007). The inland sedimentary basins consist of Mamfe, and the northern sedimentary basins of Mbere Djerem, Babouri Figuil, Logone Birni, Mayo Oulo Lere (Njieatih, 1997; Ndjeng, 1998; Ndjeng & Brunet, 1998; Njike et al., 2000; Ntep et al., 2000; Touatcha et al., 2010). Tabenken is situated some 155 km N.E. of Bamenda and belongs to the Nkambe Plateau constrained by longitudes E010˚40' and E010˚46' and latitudes N06˚27' to N06˚46' as shown in **Figure 1**. It is known to be predominantly composed of an extensive granito-gneissic Precambrian basement, overlain by diverse suites of volcanic rocks that range from basalts to rhyolites (Njilah, 1991; Tetsopgang et al., 1999) and does not belong to any of the country's sedimentary basins, but rather, has been classified under the Cameroon Volcanic line (CVL). The discovery of patches of a coal seam in association with conglomerates and arkosic sandstones within the predominantly volcanic environment of the Nkambe Plateau, at Tabenken, however, has been an aspect of curiosity since such a sequence must have been produced by major sedimentary processes.

Coal occurrence in Cameroon is rather rare but in Tabenken like in Fundong and Bali, with crystalline substrata, brown coal constitutes the second layer of sediments, overlying a conglomeratic sandstone series. Lignite lenses have also

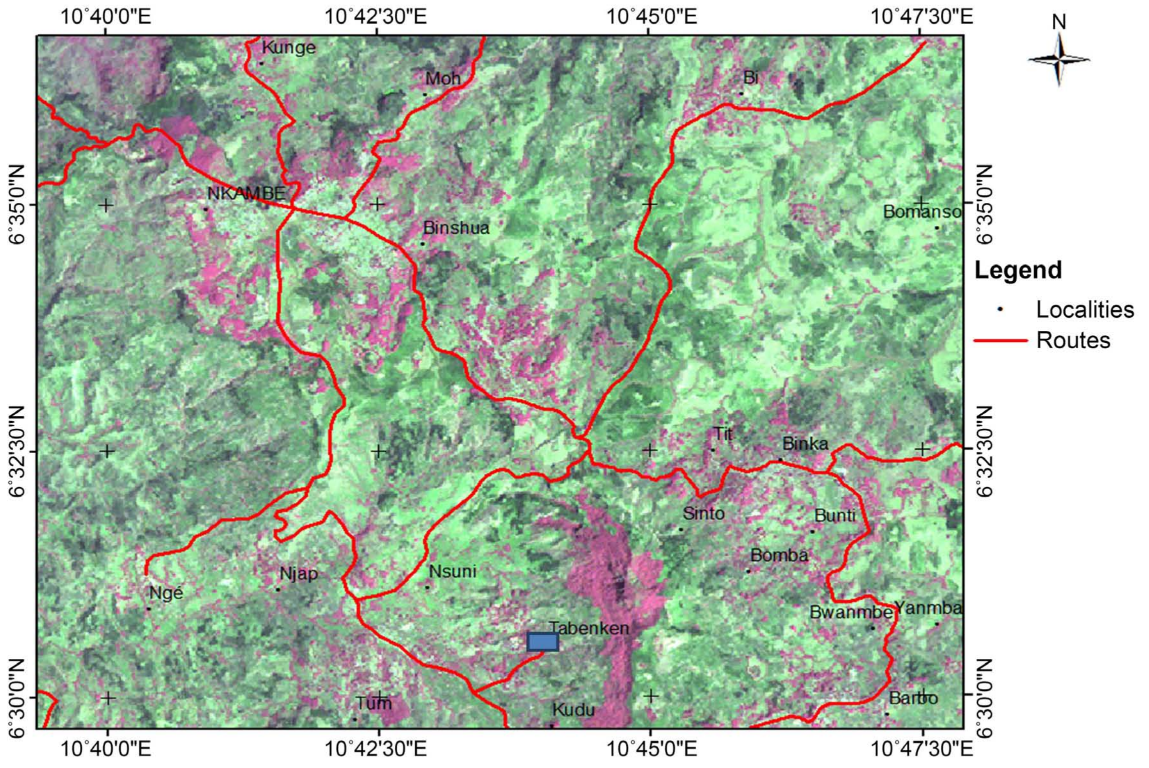

Figure 1. Location of the Tabenken.

been found in Ngoua, in the Bambouto massif in the Western Region of Cameroon (Kenfack et al., 2011). This study is very important as it will serve to improve the nation's natural resource data base and help in understanding and reconstituting the palaeo-environment of this area. The discovery of a coal seam in Tabenken, sandwiched in a crystalline terrain calls for an in-depth study in other to unravel the palaeo-depositional history of the region.

The goal of this research is to provide new insight findings on the geology of the coal seam, as well as information on the palaeo-environment of the locality. Other specific objectives are; to locate the coal seam and describe the modes of occurrence of coal and other sedimentary rocks involved, establish its elemental composition by ultimate analyses so as to establish its heat value, determine the types of sulfur present in the coal and their amounts and to use information from the coal seam and other sedimentary and volcanic rocks to reconstitute the palaeo-environment of the area.

Tabenken belongs to the Oku Volcanic Field (Oku Massif). This is a group of volcanoes based on a swell in the Cameroon Volcanic Line, located in the Oku region of the western high plateau of Cameroon. The Mt. Oku stratovolcano rises 3011 m above sea level, with a diameter of almost one hundred kilometers and contains four major stratovolcanoes; Mt. Oku, Mt. Babanki, Nyos and Nkambe plateau. The oldest rocks of the massif range from 31 to 28 million years, (Njilah, 1991) but more recent activity has also occurred with the emplacement of pyroclastic materials and ash flow tuffs. The basement comprises of alkali rhyolites and anatectic granites **Figure 2** is a map of the basement.

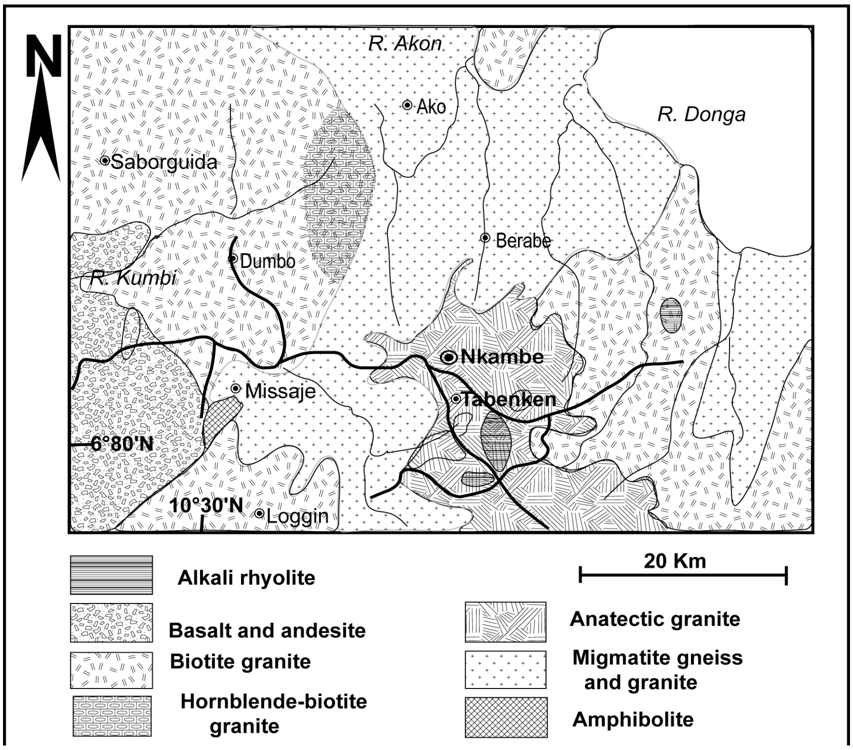

Figure 2. Geological map of Tabenken area (modified from Tetsopgang et al., 1999).

2. Field Description of the Outcrops

Tab 1 (first outcrop) is an outcrop located at N06˚29'35.9" and E010˚41'20.4". Based on the physical properties, it consists of two distinct parts; a highly hydrated upper unit and a basal unit containing coarser particles of coal and fine sand. This bed is overlain by weathered rhyolite (Figure 3). It dips in two directions and at different angles, 15˚N and into the valley wall 20˚NNE.

Tab 2 located at N06˚29'36.6" and E010˚29'36.6" is characterized by a series of loose fine grained sandstone boulders containing fragments of coal. This phenomenon can be seen on Figure 4. In some cases, the sand sized-coal particles freely mix with the sand, forming a cohesive black mass. In other cases, the coal occurs within sandstone beds forming a thin continuous layer. In another case, coal is completely enclosed within the sandstone boulders which occur along the stream channel.

Tab 3 is located at N06˚29'29.7" E010˚41'19.2" and consists of disrupted coal layers with near vertical orientations along the valley wall as seen on Figure 5. Here, a discontinuous and slightly inclined outcrop was observed. These layers consist of coal mixed with weathered rhyolites. The coal is well compacted but

Figure 3. Muddy coal bed along the river bank.


(a) (b)

Figure 4. (Left) sandstone boulder hosting petrified wood, (right) coal and sandstone blend together in a cohesive mass.

Figure 5. Disrupted coal layers occurring vertically along the stream channel.

occurs as angular fragments. These fragments blend together in a cohesive mass, but however, tend to crumble easily to touch.

Tab 4 is found at N06˚29'32.6", E010˚41'16.3", at an elevation of 1538 m. It consists of localized intercalations of coal and rhyolite flows. Thin black coal layers occur in different sizes. Some occur as thin dehydrated coal layers within the fine-grained rhyolite is seen on Figure 6. Basically, coal layers occurring in this form range in thickness from 0.5 cm to 2 cm and are inclined. A uniform coal layer of about 1.57 m thick also occurs here. Most parts of these coal intercalations dip 70˚SE and strike at 30˚NW. However, the bottom is almost horizontal and some parts appear folded.

Tab 5 located at N06˚29'31" and E010˚41'17" consists of thin layers of coal and screes. The exposed surface is basically composed of loose coal dust, coal scree at the base of the wall and as thinly spaced almost vertical layers. With a dip of 60˚WNW, the total exposed bed has a thickness of 1.40 m. This layer is loose and displays phyllytic cleavage especially those close to the surface, which are very fragile and crumble easily.

Some of the coal surfaces are coated with powdery reddish-brown cement and made up of centimetric fragments which are loosely attached to each other. The distinct units are highly compacted but easily fragmented such that no continuous layer could be sampled. The reddish brown coatings are highly penetrative causing the coal to easily breakdown into thin layers. At the base of these vertical layers is found the accumulation of scree-like coal and can be seen on Figure 7, characterized by fragments of a wide range of sizes.

Tab 6 consists of high grade coal fragmental intrusion within tuff. It is black and shiny and less hydrated. It has a glassy texture, less dense and fractures easily shown on Figure 8 along defined conchoidal planes.

Tab 7 is located at N06˚29'31.7" and E010˚41'16.8" at altitude 1552 m and consists of hydrated dense rock particles mixed with over 70% volcanic ash. This massive deposit is exposed at the face of a cliff as seen on Figure 9 and dips 15˚W.

Figure 6. Intercalation of coal in rhyolite.

Figure 7. Thin coal layers and dust outcropping along the valley wall.

Figure 8. Highly fractured high grade coal bed.

Figure 9. Massif and partially compact coal mixed with volcanic ash.

The bed is about 140 cm thick but its lateral extent cannot be estimated since it dips into the hill. It's underlain by a reddish brown palaeosoil layer and above it is a thin layer of darker soil. It is less cohesive and easily detaches into distinct blocks from the main bed. The degree of compaction, hydration and density of this deposit decreases from the bottom towards the top. It is mixed with reddish brown mud and contains roots of grass and shrubs.

The bottom of this massive bed is highly compacted, dense with a thickness of about 70 cm. It splits easily into blocks along well defined planes. This extends to about 70 cm from the base of the bed. Thin grey laminations of clay (≤1 cm) can also be found within this massive layer.

3. Analytical Methods

All the analyses (ultimate analysis and forms of sulfur analysis) on samples of coal from the TCS (Tabenken coal seam) were carried out in Standard Laboratories, Inc, Van Buren, Arkansas, USA. Each of the samples was standardised using the American Society of Testing and Materials (ASTM) standard analyses, in accordance with the International Organization for Standardization (ISO). Ultimate analysis was conducted by combusting a sample of coal in an analyzer which measures the weight percent of carbon, hydrogen, nitrogen, sulfur and ash from a coal sample. The high-temperature combustion test method for sulphur (ASTM D-4239, sub-methods A, B, and C), requires that a weighed sample be burnt in a tube furnace at a minimum operating temperature of 1350˚C in a stream of oxygen to ensure complete oxidation of sulphur-containing components in the sample. Using these conditions, all sulphur-containing materials in the coal or coke are converted predominantly to sulphur dioxide in a reproducible way. The amount of sulphur dioxide produced by burning the sample can be determined by titration.

4. Results

The elemental content based on ultimate analysis of the Tabenken coal and forms of sulphur analysis respectively are summarized in **Table 1** and **Table 2** respectively. In total, five ultimate analyses were done, one on each of the five coal samples (Tpt6-2, Tpt5-1, Tpt2-1, Tpt1-2 and Tpt5-2) to determine the percentage of fixed carbon (organic and inorganic), hydrogen, nitrogen, sulphur, oxygen and volcanic ash content. Only one sample Tpt6-2 was analysed for the forms of sulphur (sample), because in hand specimen, and from it colour it showed evidence of the presence of sulphur.

Data from chemical analyses show that the Tpt5 sample is characterized by a high carbon, low oxygen and ash contents and has physical characteristics similar to bituminous coal, whose sulfur and hydrogen contents are low. The Tpt6-2, Tpt2-1 and Tpt1-2 samples have a very high proportion of ash (>86%) and very low proportions of carbon (≤3.21). The hydrogen, nitrogen, sulphur and oxygen percentages are also relatively very low; this raises a strong question about the validity and nomenclature of the samples. Analysis for forms of sulphur reveals that only sulphate and pyritic forms are present. Organic sulphur which commonly occurs in coal is basically absent.

5. Interpretation of Results

5.1. Field Occurrence of the Table Enken Coal

Field investigation of the Tabenken coal reveals the occurrence of coal alongside other sedimentary rocks in association with volcanic material. The occurrence of patches of sedimentary rocks such the sandstone boulders and coal suggests a

Table 1. Percentage ultimate analyses of coal samples from the TCS.

Sample ID	**Tpt5-1**	**Tpt5-2**	**Tpt2-1**	**Tpt6-2**	**Tpt1-2**
Components	**% dry basis**	**% dry basis**	% dry basis	% dry basis	% dry basis
ASH	**17.56**	**17.5**	86.59	87.12	87.18
Hydrogen	**3.24**	**3.21**	1.36	1.29	1.24
Carbon	**58**	**58.14**	3.21	2.54	2.18
Nitrogen	**0.55**	**0.54**	0.01	0.03	0.02
Sulfur	**0.12**	**0.13**	0.03	0.02	0.04
Oxygen	**20.53**	**20.5**	8.8	9	9.34

Table 2. Forms of sulphur present in Tpt6-2.

Sample ID	Total sulphur (%)	Sulphate (%)	Pyritic (%)	Organic (%)
Tpt6-2	0.03	0.01	0.02	0

typical volcano-sedimentary terrain. The prevailing geomorphology however, is a direct product of volcanic activities. It can be seen that, in areas where the coal is in direct contact with the rhyolite as in the case of **Figure 6**, it occurs as dehydrated inclusions or laminae probably caused by the effect of heat from volcanic activity.

The haphazard nature of coal outcrops must have resulted from later volcanic activities that shattered the original coal beds formed in a sedimentary setting. The extensive occurrence of dark sediments and coal fragments along the Mammie valley is as a result of reworking of earlier formed coal beds by local geological processes. Most of the coal fragments are hard, well compacted and less dense. This is clear indication that they were formed under increasing temperatures and pressure through a burial process. Such a progressive increase in temperature and pressure is capable of stopping the biological processes and setting in only physicochemical processes involved in the process of coalification and is responsible for the formation of high rank coals especially within mountain ranges (Amijaya, 2005). The occurrence of nearby volcanic activity must have supplied enough heat that helped to locally increase the rank of the coal from one outcrop to another as evidenced by the fact that samples occurring as inclusions in the lava flow units show physical characteristics similar to those of anthracite.

5.2. Laboratory Results

The rank of coal was calculated from its carbon content or the heat value (obtained by ultimate analyses). The results of ultimate analyses and forms of sulphur analyses observe that the carbon and sulphur contents of the TCS vary from one sample to the other. Samples Tpt5-1 and Tpt5-2 contain 58.14% and 58% of carbon respectively. According to Bowen and Irwin (2008) this will produce 11,250 - 14,350 Btu per pound of heat upon combustion equivalent to bituminous coal. For coal of this capacity to be formed, the organic matter must have been subjected under very intense temperature and pressure conditions. With these high temperature and pressure conditions, most of the volatile constituents should have been liberated, leaving behind the carbon residue.

The sample has a total sulphur content of 0.13%. Yancey and Geer (1968) list analyses of inorganic forms of sulphur in various forms of coal around the world and these range from 0.44% to 9.01% total sulphur and only rarely will one expect to find coal in which the percentage sulphur wouldn't be included in this range. The sulphur content of this sample is unexpectedly below the "normal" low and so can be described as being insignificant.

With nitrogen contents ranging from 0.55% to 0.54%, lower than low values of nitrogen in coal suggested by Spracklin et al. (1991) which ranges from 0.7 to 2.0 wt% the coal will emit less NO_2 when burnt, hence its suitability for use. Also, the amount of nitrogen supplied into groundwater through peculation will be small hence groundwater pollution from the seam is insignificant hence doesn't pose any threat on health (WHO, 2008). The high oxygen content of 20.5% to

20.53% is an indication that they are more reactive and can be easily gasified or liquefied but unfortunately, coal with such high oxygen content is not suitable for the production of coke.

The analyzed coal samples both indicate low percentages of sulphur; (0.12%, 0.13%) which makes them suitable for combustion as the amount of SO_2 gas it will produce will be relatively small. Samples (Tpt6-2, Tpt2-1, Tpt1-2) contain 2.54%, 3.21% and 2.18% of carbon respectively which is very negligible hence of almost insignificant heating value. Carbon content of this range is not classified under any rank of coal making it difficult to accord an accurate name for any of the samples. However, looking at their high ash content, it is clear that they constitute coal ash and not coal. This coal ash could either have resulted from excessive weathering of the existing coal bed or by ignition of coal fires during the eruption, but occurring in a volcanic terrain, it is evident that it was produced by these coal fires and not weathering. Still to support this fact, highly weathered coal contains a high proportion of sulfate sulfur which instead occurs in extremely low quantities in these samples hence the ash could not have resulted from weathering. These samples contain very small amounts of sulphur; 0.2%, 0.3% and 0.4% respectively, their total sulphur contents being far below the lower limit experimented by Yancey and Geer (1968).

Despite the low calorific value of these samples, they can be exploited for their high ash content. About 43% of fly ash in the US is recycled (Dodge, 2015). The ash can be used as substitute for clay in the production of cement and as fine aggregates in blocks. It can also be used as material for paving roads, landscape repairs and as amendments for fertilizers made from municipal sewage.

The occurrence of sulphate and pyritic sulphur which are indicators of reducing and oxidizing environments respectively in the coal of this locality is an indication of quick fluctuations between reducing and oxidizing environments.

The occurrence of coal along this latitude is not only common in Cameroon; in neighbouring Nigeria, coal deposits of the Anambra basin (Onuigbo et al., 2012), more specifically those in Enugu (Olabanji, 1991) are found at almost the same latitude, with that of Enugu within the closest range. Coals of the Anambra basin like those in Tabenken have a low sulphur content, but a bulk of those in the Anambra basin are sub-bituminous. Unlike the coal seam in Anambra, the TCS was intruded by a volcanic eruption. The higher rank of some of the samples in Tabenken may be attributed to metamorphism as a result of excessive heat from volcanic activity which then transformed the coal into a higher grade. Such a phenomenon has been observed in coals of Tanjung Enim in the South Sumatra basin in Indonesia (Amijaya, 2005). In this area, andesitic sills have intruded sub-bituminous coal beds such that, coal layers close to the intrusions have been thermally metamorphosed to low volatile bituminous coal and meta-anthracite. It isn't normal to find coal within explosive volcanic environment to be rich in ash, since ash is not easily preserved in such a setting. However, a coal bearing environment which may likely be a marshy or swampy region can easily encourage the preservation of ash. Such an occurrence is very important in correlation and palaeo-environmental reconstitution since beds containing the same ash content are likely to have formed within the same period, as well as in calm environments which favor the preservation of ash (Triplehorn, 1976; Ryer et al., 1980). Hence, the likely occurrence of preserved ash in this region may be due to the fact that the area had potentials of preserving ash i.e. it was swampy before the introduction of the volcanic activity.

5.3. Palaeo-Environment

Favourable conditions for coal formation include; abundance of plant and animal material growing in a swamp and warm wet climate. This suggests that Tabenken should have experienced warm and wet tropical climate at the time of growth/death/burial of these plants. The Carboniferous Rainforest Collapse (CRC) which occurred in the Carboniferous period was an extinction event during which climate change devastated the tropical rainforests causing mass extinctions of plant and animal species. Several hypotheses have attempted to explain the CRC, some of which include climate change (Fielding et al., 2000; Herkel, 1991; Dimichele et al., 2010). Particularly, at that time, climate became cooler and drier, reflected in the rock record as the earth entered a short intense ice age. The cooler drier climatic conditions were unfavourable for the growth of rainforests and most of the biodiversity within them. Then the succeeding period of global warming reversed the climatic trend; the remaining rainforests, unable to survive the rapidly changing conditions were finally wiped out. The rainforests were finally replaced by seasonally dry biomes (Torsvik et al., 2008).

Other possible causes of the climatic changes that were strongly supported by evidence include large scale volcanicity (Benton, 2005). Looking at the geological setting of the Tabenken coal seam, this is a plausible explanation for the cause of the change in climate which led to the mass extinction of species that produced the Tabenken Coal Seam, as it is located on the North West continental segment of the CVL.

Based principally on lithofacies interpretation, the two major rock groups found in this region are igneous (plutonic and volcanic), and sedimentary. Though most of the sedimentary units have been masked by the volcanic rocks, the few that were observed can still give a clue as to the past environment. Conglomerates and sandstones besides coal are the sedimentary rocks common in this area. However, these rocks do occur as discontinuous units or boulders and in different locations so, cannot easily be situated in time and space. Most of the coal fragments and petrified wood observed occur as inclusions in the sandstones; a rough indication that they are autochthonous. The association of these sandstones with conglomerates indicates a typical continental deposit. This implies the Tabenken coal was formed in a typical continental setting, probably in an ancient basin before the area experienced the major episodes of volcanism and upliftment.

The continental origin of this deposit is also supported by the occurrence of an extensive granite wash, as well as tuff (Amijaya, 2005). Though the sequence of events cannot easily be put in time and space due to lack of any biostratigraphic or radiometric data, as well as sequence destruction associated with volcanism, it is logical to say that the environment would have been small sedimentary basin, before it was transformed into a volcanic terrain. Based on this model, the erupting magma must have intruded the sedimentary basin, whereby part of it was digested by the magma and some portions shattered or overturned by the volcanic activities.

Though the coal found here is mostly bituminous, it is possible that, sub-bituminous coal or meta-anthracite be found here. This is a common phenomenon in most areas where a low rank coal basin is affected by volcanic activities and some of the coal is subjected to thermal metamorphism.

Though it's difficult to establish the stratigraphic sequence of the Tabenken area due to some of the difficulties highlighted above: the absence of radiometric and biostratigraphic data as well as the limited exposures of sedimentary units. It is however, possible to use the geometric relationship of the various lithofacies as well as facts established by related theories and principles to establish the litho-sequence of the TCS. The lithostratigraphic sequence of this area can be broadly divided into three major units. The oldest of these units is represented by the Precambrian granites (510 ± 25 ma), a middle sedimentary unit of undetermined age, and an upper unit composed of mostly Tertiary volcanic rocks (28 - 31 ma). The coal deposit therefore is younger than the Precambrian basement but older than the Tertiary volcanic rocks (**Figure 10**). It should be noted that, the coal

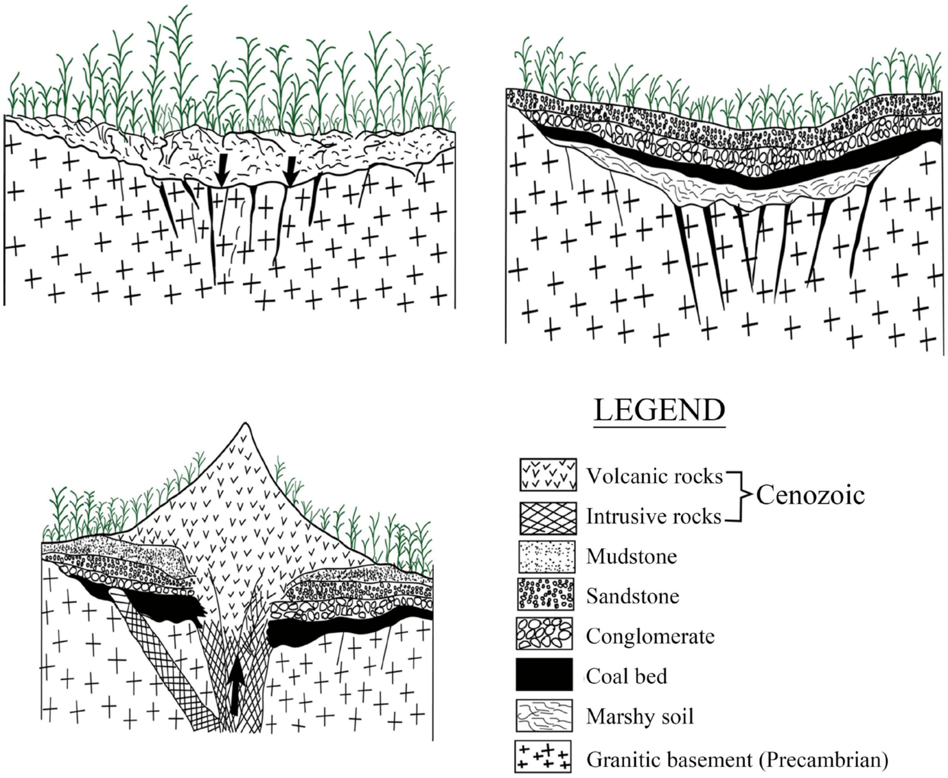

Figure 10. Schematic representation of palaeo-geology of the TCS.

exposures observed may just be patches of beds brought up by the volcanic upliftment. The undisturbed sequence may be deeply buried and can only be properly investigated using geophysical means. In the absence of radiometric and biostratigraphic data, the principle of uniformitarianism can be used to establish the relative ages of the lithofacies as illustrated on **Figure 10**; from the included fragment principle, it is logical to say that the coal is older than the volcanic rocks containing it. The coal, as well as petrified wood also occurs as inclusions within sandstone boulders and it can be said to be relatively older than these boulders. Sand grains mixed with coal in certain sites within the rhyolitic rocks give a clear indication that the sandstone is equally older than the rhyolitic rock. Considering the aspect of sedimentation; graded bedding which states that sedimentary strata are deposited with coarse grains at the bottom progressively succeeded by finer grains, the conglomerates were therefore deposited before the sandstones. The very conspicuous clay beds observed are therefore a product of weathering of the rhyolitic rocks in the area. Since all the sedimentary facies are older than the rhyolites, it is therefore clear that the process of sedimentation took place before the volcanic eruption.

6. Summary and Conclusion

The goal of this research was to provide a new insight on the geology and chemistry of the Tabenken coal and deduce its palaeodepositional setting. These research findings have shown that, the TCS is composed of bituminous coal which has been affected by volcanic activities as well as reworking events of erosion and weathering. Careful examination of the different lithofacies reveals that the coal was formed in a typical continental environment which was later modified into an uplifted volcanic terrain. The coal is most likely to have formed at depth before being pushed to the surface as a result of instability associated with rising magma, modifying its chemistry and geometry. Hence, the precursor coal as well as its other sedimentary association (sandstone and conglomerates) is older than the volcanic event whose age has been established as 31 to 28 million years but younger than the Precambrian basement.

With a carbon content of about 58%, and a high volatile content, this coal can easily be liquefied or gasified. Though sulphur analysis cannot be considered representative enough due to the anomalously high ash content of the sample analyzed, the low values obtained implies such a coal can produce less SO_2 after combustion. The high ash content that characterizes this zone is believed to have come from the associated explosive volcanic activity of this region. This volcanic activity played a dominant role in destroying part of the coal and masking most of it making any direct sampling difficult if not impossible. Results of this research have further shown that, a marshy palaeodepositional environment played a major role in the preservation of ash from the volcanic activity. This locality was a major palaeo-basin that has been modified by recent volcanic uplift.

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Conflicts of Interest

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

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