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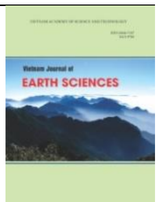

Hydrogeology and origin of waters of the Panyam Volcanic Line springs, Jos Plateau, Nigeria

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ABSTRACT

The PVL springs are used for both domestic and agricultural purposes. The seepage from the springs has resulted in producing a large expanse of wetlands and is therefore intensively use for dry season farming. The aim of this study was to determine the hydrogeological, hydrochemical characteristics, origin and their suitability for domestic and irrigation. The hydrogeology of the springs was determined by field mapping. The physico-chemical parameters were determined in the field and by laboratory methods. For the cation and anion analysis the ICP-MS and the wet methods were employed respectively. The stable isotope composition of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) were analyzed by Isotope Ratio Mass Spectrometer. The hydrochemical analysis revealed that the PVL springs waters are generally neutral with an average pH value of 7.3. The average TDS and EC values are 127.8mg/l and 246µs/cm respectively. These values fall within fresh water class. The average Mg^{2+}, Ca^{2+}, Na^{+} and K^{+} cation concentration values are 16.3mg/l, 15.8mg/l, 10.8mg/l and 5.58mg/l respectively. The average anions concentration of HCO_3^-, SO_4 and Cl^- are 140mg/l, 8.6mg/l and 3.4mg/l respectively. Piper trilinear diagram show that the spring waters is predominantly Mg-Ca-HCO_3 water type with potable qualities based on WHO drinking water standards. The sodium Adsorption Ratio (SAR) and Sodium Soluble Percentage (SSP) values range between 0.44 to 0.84 and 26.4 to 54% respectively and falls within irrigation quality standards. Stable isotope compositions of $\delta^{18}O$ and $\delta^{2}H$ ranges from $-3.6_{0/00}$ to $-4.9_{0/00}$ and $-20_{0/00}$ to $-28_{0/00}$ respectively falls within the meteoric water composition. This is further affirmed by the $\delta^{2}H$ versus $\delta^{18}O$ plot on the correlation diagram with Standard Meteoric Water Line.

Keywords: Hydrogeology; hydrogeochemistry; origin; Panyam Volcanic Line springs.

1. Introduction

Springs are points at which water flows out from an aquifer to the earth surface (La Moreaux and Tanner, 2001). The forcing of the spring to the surface can be attributed to a confined aquifer where the recharge area of the spring water table rests at a higher elevation than the outlet (en.m.wikipedia.org, https://www.britanica.com). Generally, springs are classified into 5 classes namely- seepage spring, fractured spring, tubular spring, warkey holes and karst springs (en.m.wikipedia.org). Springs are classified also by the volume of their discharge

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(waterdata.usgs.gov). In many volcanic regions, volcanic springs flow out at or some distance away at the base of piles of volcanic ejecta material through-fractured basalts and/or sub-basalt alluvium (Longpia, 2003; Siebe et al., 2007; Lar and Usman, 2012).

The Panyam Volcanic Line (PVL) comprises of seven volcanoes aligned in a NNE-SSW direction stretching over a distance of about 20 km. The PVL volcanoes are namely Kerang I & II (Twin volcanoes), Timjahas, Pidong, Ampang, Niyes and Hiktup volcanoes and are characterized by craters in their summit (Schoeneich and Ugodulunwa, 1994; Lekmang, 2019). Volcanic springs flow out at the foot or near the volcanic cones and forming large pools and flows to form minor streams and/or joining major drainage system like the River Ndai and River Bwonpe (Fig. 1). The springs are cold volcanic spring types. Stable isotope composition of some of the water resources (crater lake and Bwonpe volcanic spring) show they are meteoric in origin (Lar et al., 2020). The Bwonpe volcanic spring flows out at about 1.5 km east of Pidong volcano, and flows southeastwards and joints the River Bwonpe forming part of the upper reaches of the River Shemankar basin. The slight basement uplifts around the Pidong volcano trending south-northwards forms the watershed separating the upper River Ndai and upper River Shemankar catchments. The springs form large wet lands along their flow path. The springs are directly used for drinking and the wet lands are use for irrigation purposes by the local population. The volcanic springs and crater lakes have attracted many tourists and even the sitting of the mineral bottling plant by Spring Water of Nigeria (SWAN) at the foot of the Kerang volcano. The hydrogeology and geochemistry of the PVL springs have not been properly documented. This research is aimed at investigating the detail hydrogeology/geochemistry, origin and the suitability of all PVL spring waters for drinking and irrigation use.

The average yearly rainfall around the Panyam Volcanic Line is about 1200mm/yr (Longpia, 2003; Gusikit, 2010). The average annual recharge/infiltration in the upper River Ndai basin within the Ampang-Kerang axis is about $1.73 \times 10^6 m^3$ (Longpia, 2010; 2013). The groundwater recharge from rainfall is through the permeable and semi-permeable volcanic ejecta materials where most of the volcanic cone or summit stands out at 1400-1500masl and flow in radial form down the hydrologic gradient (Schoeneich and Ugodulunwa, 1994).

2. Geological setting

The Panyam Volcanic Line (Fig. 1) is part of the Jos Plateau volcanic region and lies between latitude 9°15' to 9°30' and longitudes 9°07' to 9°13' and consists of a series of seven (7) dormant/extinct volcanoes aligned in a NNE-SSW direction (Lar et al., 2004). The alignments of the volcanic cones follow the regional structural lineament patterns (Lar et al., 2004). The volcanoes erupted through the host medium grained granite gneiss rocks. The volcanic cones are characterized by volcanic craters which are well preserved. The cones consist of piles of basalts, pyroclastic materials with high proportion of fragments of basement rocks and/or pulverized granites, scoria and ash (Lekmang, 2019). The mineralogical constituents or composition of the volcanic rocks consist of olivine, pyroxene, plagioclase (Labradorite) and accessory minerals (ilmente/magnetite) (Gusikit, 2010; Lar and Gusikit, 2015; Lekmang, 2019).

The mineralogic compositions of the basaltic rocks of the volcanoes of the Panyam Volcanic Line range from labradorite to bytomnite (Lar et al., 2013; Lekmang, 2019). Generally, volcanic eruption processes and/or any igneous process are known to be associated with minerals and chemical elements coming from mantle sources (Lar et al., 2015).

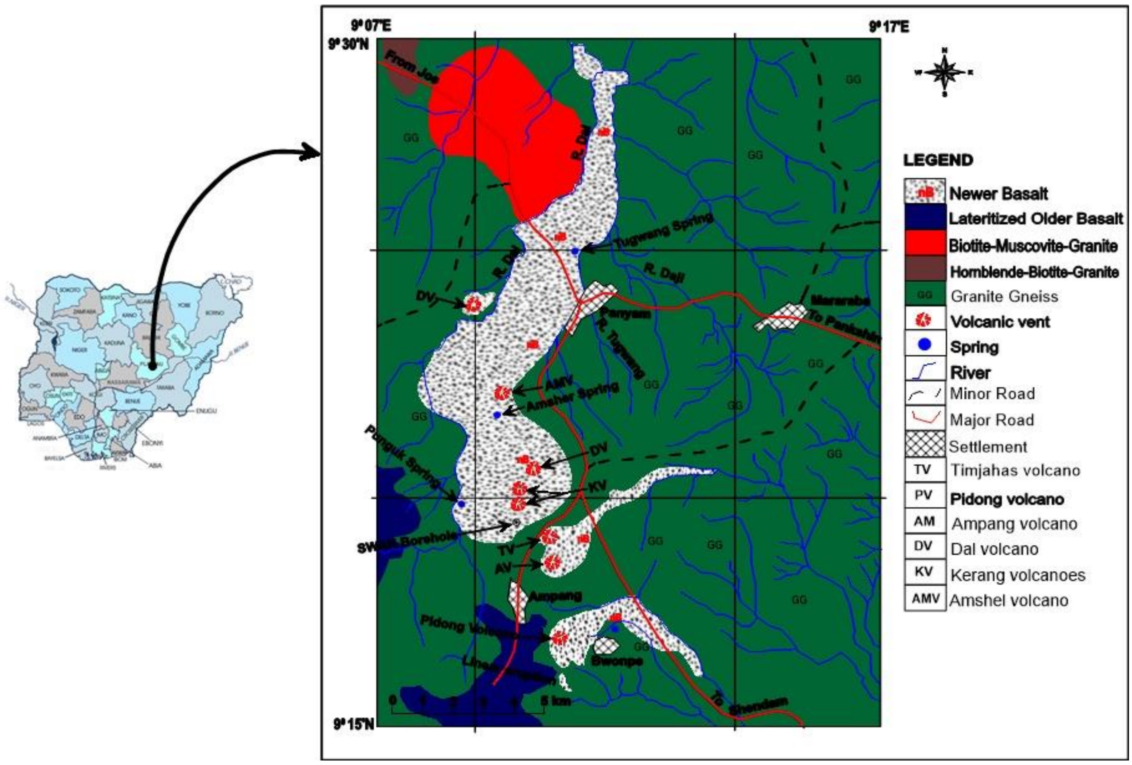

Figure 1. Location and Geological map of Panyam Volcanic Line

3. Methods

3.1. Fieldwork

The fieldwork involved hydrogeological mapping of the spring sites to tie it to the overall geological setting of the volcanic region; geo-electric sounding using ABEM Terameter 1000 series to determine sub-surface geo-electric layer/sequence around the spring areas; spring flow-discharge measurement using float method; spring water sampling and field measurement of physical parameters of electrical conductivity (EC), total dissolved solids (TDS), pH and temperature (T) using a Hana instrument combined water proof pH/TDS/EC/ temperature tester.

3.2. Sample preparation and laboratory analysis

The spring water samples were collected in 100ml plastic bottles in duplicates. 0.1m nitric acid was added to the water in the sample bottles for calcium analysis to prevent cation precipitation and/or biological growth. The spring cation and anion concentration was determined by ICP-MS and titration methods at Veritas Minerals Laboratory, Canada and Geochemical Laboratory of the University of Jos, Nigeria respectively. The isotopic composition of the δ^2H and $\delta^{18}O$ were measured using a Continuous Flow Isotope Ratio Mass Spectrometer (CF-IRMS) at Queens Faculty for Isotope Research at the University of Ontario, Canada with VSMOW and VSLAP as reference materials. The results are in per mill notation with accuracy standard deviation of 0.5 and 5% for $\delta^{18}O$ and $\delta^{2}H$ respectively.

4. Results

4.1. Hydrogeology of the PVL springs

All the volcanic springs of the Panyam Volcanic Line flows out at or near the associated volcanic cones through fractured basalts and/or sub-basalt alluviums (Figs. 1, 2). Groundwater in the area is recharged mainly from the abundant rainfall (≥ 1200m/yr) at an altitude of over 1300-1400masl and infiltrates into the permeable and semi permeable volcanic ejecta material piles and flows down the slope and discharges through the springs. All the springs flow out through fractured and jointed basalts and/or sub-basalt alluviums. The Punguk spring (Kerang volcano) flows out in fractured basalts and sub-basalt alluvial layer at the incised section of the upper River Ndai at Sohon Kerang (Fig. 1). All the PVL springs comprising of Bwonpe Volcanic Spring, Amshall, Ampang, Niyes, Hiktup and Tugwang) flow out mainly in fractured basalts in seepage form with the exception of Punguk which flows out in fractured jointed basalts and sub-basalt alluvium in a gushing form (Fig. 2).

Figure 2. The Panyam Volcanic Line springs in gushing and seepage forms: a-Punguk spring (Kerang volcano); b-Tugwang spring (Hiktup volcano); c-Amshall spring (Dutsin volcano); d-Niyes spring (Niyes volcano); e-Ampang spring (Ampang volcano); f-Hiktup spring in fractured granite (near Hiktup volcano)

The upper River Ndai at Sohon Kerang flow in between the contact of the basalts and the granite basement. The Punguk spring gushes out on the eastern flank of the river within the jointed and fractured basalts and sub-basalt alluvium to flow into the upper River Ndai.

A hydrogeologic correlation of the SWAN exploratory borehole located at the foot of the Kerang volcanoes and Punguk spring section at Sohon Kerang (Fig. 3) revealed a continuous stretch of sub-basalt alluvial bed. The alluvium consists mainly of ‘baked’ sandstones intermixed with clays ‘sandwiched’ between an upper basalt layer and undulating granite basement.

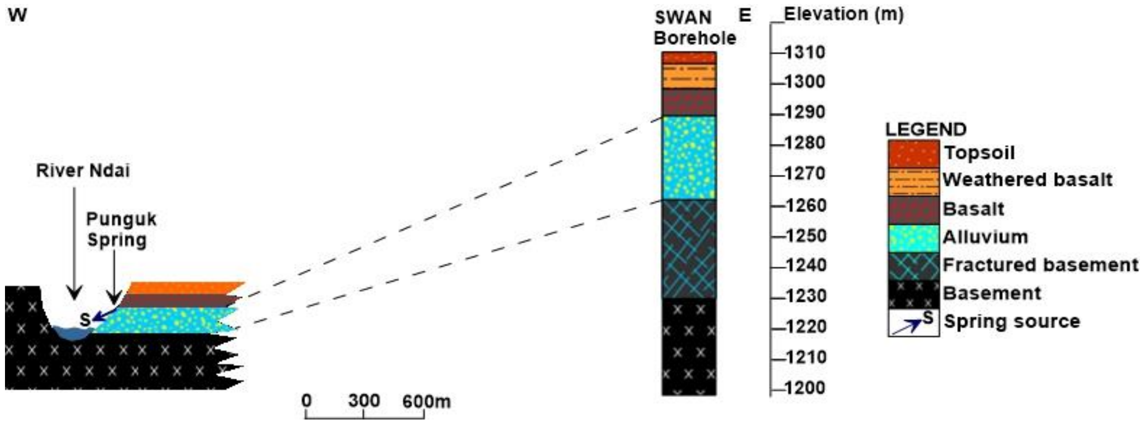

Figure 3. Hydrogeologic correlation of Punguk Spring at the River Ndai section at Sohon Kerang and SWAN Borehole

4.2. Geo-electric survey across the spring sites

Geo-electric investigation using geo-electrical resistivity sounding techniques around some selected spring sites at Punguk and Bwonpe Volcanic spring revealed 3-6 sub-surface geo-electric layers/lithologic units around the spring sites (Figs. 4, 5). The geo-electrical sounding model curve interpretation revealed mainly topsoil (0 to 2.5m), weathered /fractured basalts (2.5 to 35m), sub-basalt alluvium (5 to 15m) and basement (0.5 to ∞m) and characterized by variable resistivity value range of 43 to 530 ohm-m, 120 to 170 ohm-m, 61-73 ohm-m and 100 ohm-m respectively (Table 1).

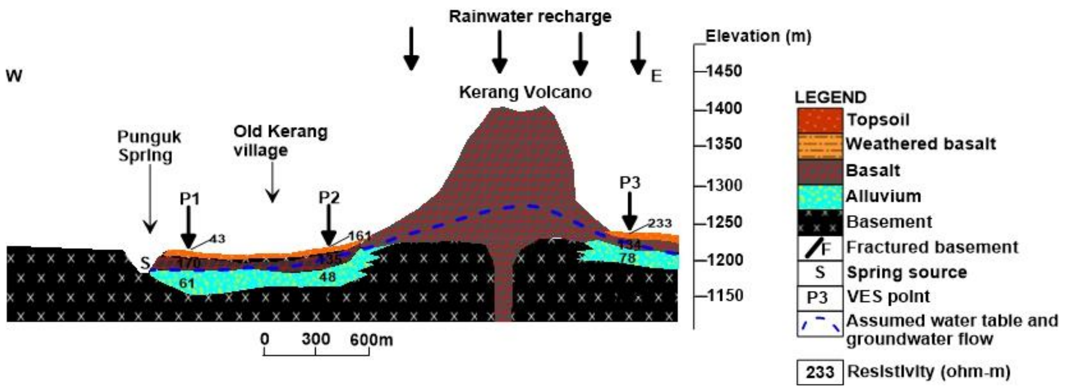

Figure 4. Geo-electric section along west-east direction (Punguk spring-Kerang volcano axis)

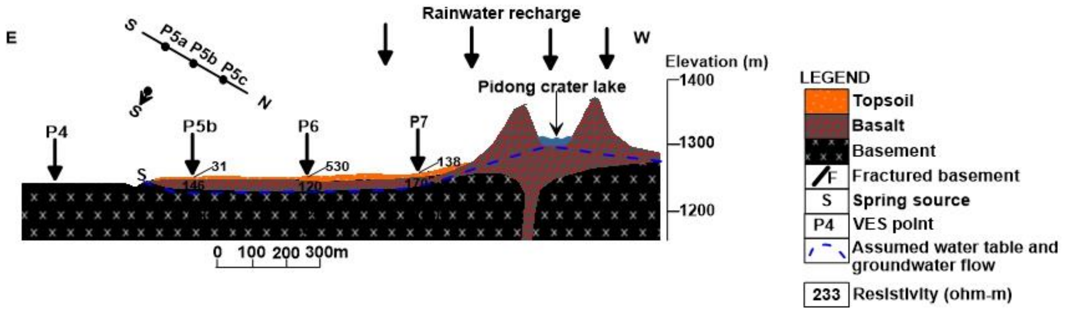

Figure 5. Geo-electric section along east-west direction (Bwonpe volcanic spring-Pidong volcano axis)

Table 1. Geo-electrical resistivity soundings interpretations at Punguk (Kerang volcano) and Bwonpe volcanic (Pidong volcano) spring sites

S/No.	Spring location	VES No.	Depth (m) $d1/d2 \ldots dn^{-1}$	Resistivity (ohm-m) $\ell 1/\ell 2 \ldots pn$	Curve type
1	Punguk	P1	1.5/3.2/9.1/16.1/42.2/∞	43.6/4.4/170/61.1/5.8/137	HKH
2	Punguk	P2	1.1/3.7/12.1/32.6/∞	161/82/4.7/137/48	HK
3	Punguk	P3	2.6/6.3/11.7/15.6/29/38/∞	233/13/80/101/134/79/73	HK
4	Bwonpe volcanic spring	P4	1.6/18.2/27/∞	294/32/198/600	H
5	″	P5a	1.8/10.5/30/??	400/25/398/685	H
6	″	P5b	1.5/7.3/21.1/??	374.6/21.2/146.6	
7	″	P5c	2.7/11.8/35.8/∞	210/58/179/400	H
8	″	P6	0.8/2.11/11.2/15.2/38.5∞	530/152/28/82/120/42.5	HK
9	″	P7	1.5/3.8/7.5/21/??	138/48/170/100	HK

4.3. Spring flow measurement

The hydrograph (Fig. 6) displays the flow-discharge regime of the PVL springs. The minimum and maximum flow rates range between 0.009m^3/sec and 0.25m^3/sec with the Amshall and Hiktup springs having the highest flow-discharge rates. Generally, all the spring flow-discharge increases slightly from the month of June, at the onset of the rainy season and reach their maximum height in August at the peak of the rainy season. The flow-rates gradually decrease thereafter to maintain a near constant base flow from January through the rest part of the year. The average flow-discharge for the BVS, Punguk, Ampang, Niyes, Hiktup and Tugwang are 1,035,432m^3/yr, 843 m^3/yr, 588m^3/yr, 1,390,737m^3/yr, 468,046m^3/yr, 204,721m^3/yr and 508,255m^3/yr respectively (Fig. 6). The combined annual spring flow is about 4,450,779m^3/yr.

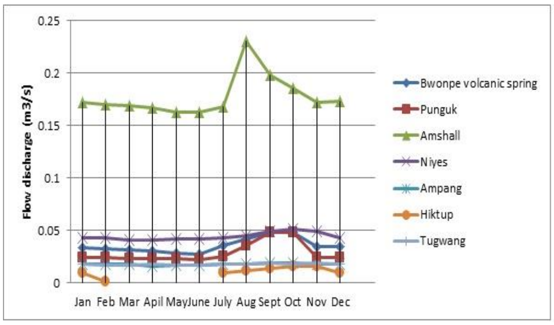

Figure 6. Hydrograph of the Panyam Volcanic Line springs for the year 2019

4.4. Hydrogeochemical Anaysis

The physico-chemical analyses of the PVL springs are shown in Table 2.

Table 2. Physico-chemical parameters of the Panyam Volcanic Line springs

Spring	Spring type	Date of sampling	pH	Temperature (°C)	EC (µs)	TDS (ppm)	Mg^{2+} (mg/l)	Ca^{2+} (mg/l)	Na^+ (mg/l)	K^+ (mg/l)	Cu (mg/l)	Al (mg/l)	Pb (mg/l)	Fe (mg/l)	SO_4^{2-} (mg/l)	Cl– (mg/l)	HCO_3^- (mg/l)	$\delta^{18}O$	δ^2H
Bwonpe (Pidong volcano)	Seepage	26/2/2019 20/9/2019	7.86 6.95	26.4 20.7	272 258	136 124.5	20.15 19.35	16.27 12.06	10.49 10.3	5.03 3.96	0.005	0.393	0.002	1.3	9.40 7.95	5.96 3.89	145.4 127.8	-4.7	-26
Ampang (Ampang volcano)	Seepage	‘’	7.51 7.11	23.4 21.5	213 200	105 98.1	14.64 12.8	14.72 10.5	7.97 6.3	5.42 4.12	0.015	0.076	0.001	0.050	9.25 9.2	1.99 2.5	125.24 110	-4.4	-25
Punguk (Kerang II volcano)	Gushing	‘’	7.47 7.03	24.3 22.5	337 275	169 159	27.08 25.7	27.64 24.5	13.39 11.8	5.69 4.35	0.0022	0.008	0.007	0.0001	9.25 8.3	1.99 1.45	183.82 190	-4.9	-27
Amshall (Dutsin volcano)	Seepage	‘’	7.41 7.07	25.2 21.0	290 240	145 140	20.83 21.5	16.51 13.2	12.12 11.11	7.40 6.3	0.0018	0.008	0.006	0.0001	9.00 8.68	7.94 5.83	155.5 142.5	-4.9	-28
Nyes (Niyes volcano)	Seepage	‘’	7.58 7.11	25.5 24.5	337 315	166 170	24.82 23.2	17.53 16.2	13.64 12.00	8.22 7.5	0.0013	0.006	0.001	0.0001	8.50 7.05	3.97 2.65	169.66 150.9	-4.9	-27
Hiktup (Ndai volcano)	Seepage	‘’	6.92 6.97	20.7 24.4	112 100	55 65	3.23 5.5	9.02 8.5	10.05 9.35	3.90 3.59	0.0021	0.009	0.0003	0.22	9.60 7.50	1.99 1.52	72.72 73.20	-3.6	-20
Tugwang (Ndai volcano)	Seepage	“	7.68 7.21	26.5 25.5	338 316	167 171	24.3	18.5	12.3	7.1	0.00018	0.0014	0.0001	0.18	7.5	3.2	178	-48	- 27

4.4.1. Bwonpe Volcanic Spring (Pidong Volcano)

The measured physical parameters of pH, temperature, electrical conductivity (EC) and total dissolved solids (TDS) showed the values range from 6.95 to 7.86, 20.7 to 26.4°C, 258 to 272µs/cm and 124 to 136mg/l respectively. The average geochemical concentration for the cations of Mg^{2+}, Ca^{2+}, Na^+ and K^+ are 19.75mg/l, 14.165mg/l, 10.39mg/l and 4.51mg/l respectively. The anions of SO_4^{2-}, Cl^- and HCO_3^- have concentration values of 8.67mg/l, 4.92mg/l and 136.6mg/l respectively. The isotope compositional values for oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H) are -4.7$_{0/00}$ and -26$_{0/00}$ respectively.

4.4.2. Ampang Volcanic Spring (Ampang Volcano)

The compositional values for physical parameters of pH, temperature, electrical conductivity (EC) and total dissolved solids (TDS) of the spring water range between 7.11 and 7.51, 21.5, and 23.4°C, 200 and 213µs, 98 and 105ppm respectively. The compositional isotope values for oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H) are -4.4$_{0/00}$ and -25$_{0/00}$ respectively.

4.4.3. Punguk Spring (Kerang I Twin Volcano)

The compositional values for physical parameters of the spring's pH, temperature, electrical conductivity (EC) and total dissolved solids (TDS) range between 7.08 and 7.48, 22.5 and 24.3°C, 275 and 337µs/cm, 159 and 169ppm respectively. The average geochemical concentration values for the cations of Mg^{2+}, Ca^{2+}, Na^+ and K^+ range from 22.6 to 24.08mg/l, 24.5 to 27.4mg/l, 11.8 to 13.39mg/l and 4.35 to 5.69mg/l respectively. The anions of SO_4^{2-}, Cl^- and HCO_3 range from 8.3 to 9.25mg/l, 1.45 to 1.99mg/l and 183.8 to 190mg/l respectively. The isotopic composition of the oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H) of the spring water are -4.9$_{0/00}$ and -27$_{0/00}$ respectively. The stable isotope compositional variations (Table 2) and spring water $\delta^{18}O$ vs δ^2H and SMOW correlation diagram (Fig. 8) springs display compositional similarity with the exception of the Hiktup spring. The Hiktup spring distinctively flow out from fractured granite gneiss while the rest flows out from volcanic ejecta materials.

4.4.4. Amshall Spring (Kerang II Volcano or Dutsin Volcano)

The compositional values for physical parameters of pH, temperature, electrical conductivity (EC) and total dissolved solids (TDS) of the spring water range between 7.07 and 7.41, 21 and 25.2°C, 240 and 290µs/cm, 140 and 145ppm respectively. The geochemical concentration of the cations of Mg^{2+}, Ca^{2+}, Na^+ and K^+ range between 20.83 and 21.51mg/l, 13.2 and 16.51mg/l, 11.11 and 12.12mg/l, 6.3 and 7.40mg/l respectively. The anion concentration of SO_4^{2-}, Cl^- and HCO_3 ranged between 8.68 and 9.00mg/l, 5.81 and 7.94mg/l and 142.5 and 155.5mg/l respectively. The oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H) composition of the spring water are -4.9$_{0/00}$ and -27$_{0/00}$ respectively.

4.4.5. Niyes Spring (Niyes Volcano)

The compositional values for physical parameters of the spring's pH, temperature, electrical conductivity (EC) and total dissolved solids (TDS) of the spring water range between 7.11 and 7.58, 24.5 and 25.5°C, 315 and 337µs, and 166 and 170ppm respectively. The geochemical concentration of the cations of Mg^{2+}, Ca^{2+}, Na^+ and K^+ range between 23.2 and 24.82mg/l, 16.2 and 17.53mg/l, 12.00 and 13.64mg/l, 7.5 and 8.22mg/l respectively. For the anions of SO_4^{2-}, Cl^- and HCO_3, the concentration range between 7.05 and 8.50mg/l, 2.65 and 3.97mg/l, 150.9 and 169.66mg/l. The stable isotope of oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H) composition are -4.9$_{0/00}$ and -27$_{0/00}$ respectively.

4.4.6. Hiktup Volcanic Spring (Ndai Volcano)

The spring's physical compositional values in terms of pH, temperature, electrical conductivity (EC) and total dissolved solids (TDS) range between 6.87 and 6.92, 20.7 and 24.4°C, 100 and 112µs/cm and 50 and 65ppm respectively. The geochemical concentration analysis of the major cations of Mg^{2+}, Ca^{2+}, Na^+ and K^+ show the values range between 3.23 and 5.5mg/l, 8.5 and 9.02mg/l, 9.35 and 10.05mg/l, 3.09 and 3.90mg/l respectively. The geochemical concentrations of the anions of SO_4^{2-}, Cl^- and HCO_3^- range between 7.50 and 9.60mg/l, 1.52 and 1.99mg/l, 72.72 and 73.20mg/l respectively. The oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H) are $-3.6_{0/00}$ and $-20_{0/00}$ respectively. These values are comparatively lower than the rest of the volcanic springs. It is observed that spring flows mainly within the granite gneiss rock near the contact between granite gneiss and the volcanic rocks.

4.4.7. Tugwang Spring

The spring's physical compositional values of pH, temperature, electrical conductivity (EC) and total dissolved solids (TDS) range between 7.21 and 7.78, 25.5 and 26.5°C, 316 and 338µs/cm, 157 and 171mg/l respectively. The geochemical analysis for major cations of Mg^{2+}, Ca^{2+}, Na^+ and K^+ are 24.3mg/l, 18.5mg/l, 12.3mg/l and 7.1mg/l respectively. The oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H) compositional values of the spring water are $-4.8_{0/00}$ and $-27_{0/00}$ respectively.

4.5. Groundwater types/facie and hydrogeochemical element sources

The average cations and anions of the PVL springs waters were plotted on a Piper Trilinear diagram (Fig. 7). The diagram shows the ionic compositions are concentrated within the > 60% ($Mg^{2+}$and Ca^{2+}) and 80% (CO_3^{2}- and HCO_3^-) quadrants. The dominant cation and anion are Mg^{2+} and HCO_3^- ions respectively. However, ionic compositions of the cations of Na^+, K^+, SO_4^{2-} and Cl^- constitute ≤ 20% of the ionic composition. The predominant groundwater facie type is the $Mg\text{-}Ca\text{-}HCO_3$ type. The spring waters cation and anion abundance are in the order of $Mg^{2+} > Ca^{2+} > Na^+ > K^+$ and $HCO_3^- > SO_4^{2-} > Cl^-$.

The Gibbs (1970) diagram is one of the main determining factors (processes) in establishing the relationship of water composition and aquifer lithological characteristics. The Gibbs diagram is a plot of the ratio of $Na^+ + K^+/Na^+ + K^+ + Ca^{2+}$ versus total dissolved solids and/or $Cl^+/Cl^+ + HCO_3^-$. The Gibbs diagram for PVL springs are as shown in Fig. 8. The diagram shows that the PVL spring waters fall predominantly within the water-rock dominance zone. This implies that the rock dissolution with water is dominant. This is reflected in the dominant cations of $Mg^{2+} > Ca^{2+} > Na^+ > K^+$ in the spring waters.

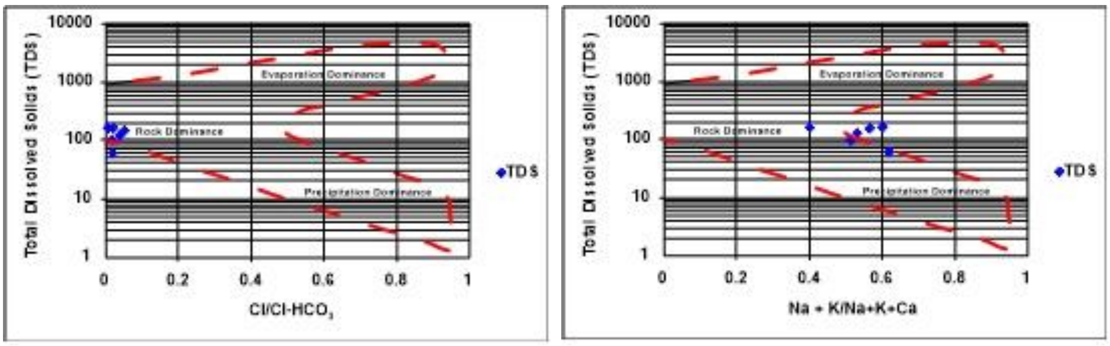

Figure 7. Panyam line volcanic spring: mechanism controlling groundwater chemistry (after Gibbs 1970)

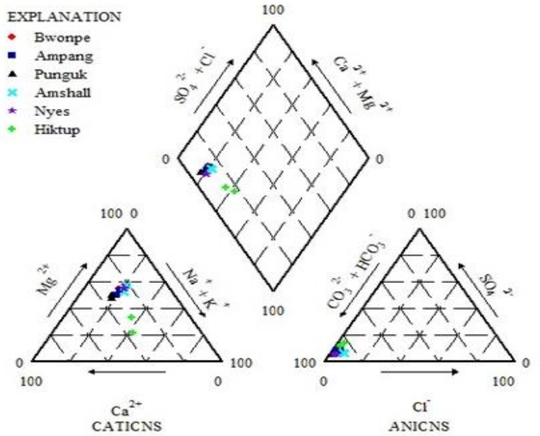

Figure 8. Piper Trillinear diagram for the Panyam Volcanic Line springs

4.6. Results of Oxygen and Hydrogen Isotope

The compositions of the stable oxygen-18 and deuterium isotopes of the springs are shown in Table 2. The δ^2H and $\delta^{18}O$ values of the springs were plotted with reference to the Vienna Standard Mean Ocean Water Line (V-SMOWL) (Fig. 9). All the values plotted on or clustered around the Standard Meteoric Water Line. The δ^2H and $\delta^{18}O$ negative values conform to those derivable from meteoric water and this is further affirmed by the plot on the SMOWL in the δ^2H and $\delta^{18}O$ correlation diagram.

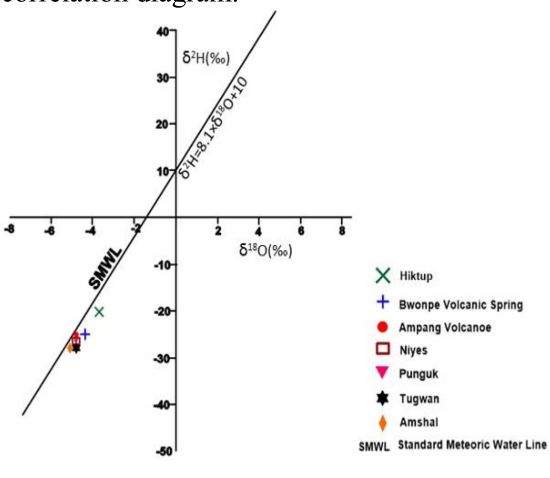

Figure 9. $\delta\,^2H$ versus $\delta\,^{18}O$ plot of PVL springs waters correlation with Standard Meteoric Water Line

5. Discussions

5.1. Hydrogeology of the PVL Springs

The hydrogeology of the PVL springs reveals that the groundwater recharge to the springs are mainly from infiltration from rainfall through the permeable and semi permeable volcanic ejecta materials, which stands out at about 1500masl and flow in radial form down the hydrological gradient and discharges through the springs in seepage or gushing form at the foot or near the volcanic cone through fractured basalts, base of volcanic ejecta piles and/or sub-basalt alluvium. The PVL springs can be classified as fractured and seepage spring types (en.m.wikipedia.org; https//:www.britanica.com). The Punguk is the only spring that flows out in gushing form. These volcanic spring types are also seen in the Biu volcanic region (Lar & Usman, 2012), Jangapeo region, Mexico (Siebe et al., 2017). The correlation of the Punguk spring at the River Ndai section at Sohon Kerang with sub-basalt lithologic unit of the SWAN exploratory borehole, evidently show the existence of a prevolcanic alluvium within a river bed prior to the eruption of the Kerang volcano. The Panyam Volcanic Line areas were characterized by prevolcanic valleys/rivers and later filled by basaltic lava flows of the PVL volcanic eruptions (Schoeneich and Mbonu, 1991; Schoeneich and Ugodulunwa, 1994). The volcanic eruption modified the immediate surrounding topography (Schoeneich and Ugodulunwa, 1994).

The continues flow rates of over 4.451×10^6 m^3/yr through the PVL springs is suggestive of a huge groundwater reservoir within the shallow and deep groundwater circulation system. This value tends to agree with the hydrograph analysis of the River Ndai basin within the Ampang-Kerang volcanic axis of about $1.73\times10^6 m^3$/yr

(Longpia, 2003). The PVL springs flow-discharge ranges between 0.009 and 0.2 m^3/s and this flow-discharge values fall within the 3rd magnitude scaling order of spring flow-discharges (waterdata.usgs.gov).

A geologic/geo-electric sections cutting across the volcanic cones and the springs sites revealed 3 to 5 geo-electric layers/lithologic units (Figs. 4, 5) consisting of Topsoil, weathered/fractured basalts, sub-basalt alluvium and fresh or fractured granite basement with variable resistivity values (Table 1). The rain infiltrates through the semi permeable and permeable weathered/fractured basalts and granite and forms the medium and deep ground water circulation which later flow out as springs around the lower elevations (Figs. 4, 5).

5.2. Hydrochemical composition and origin of the PVL springs

From the physico-chemical parameters of the spring (Table 2), the average TDS and pH values of 7.26 and 127.8mg/l for the PVL springs show that the spring waters are characteristically neutral and can be classified as fresh and soft due to its low mineralization (Lake Chad Basin Commission, 2010; Fetter, 1990). Also, the low mineralization in the spring waters is indicative of short or limited residence time (Talabi, 2013). The average major cations (Mg, Ca, Na and K) are 16.3mg/l, 15.8mg/l, 10.8mg/l, 5.58mg/l while the aniona are 173mg/l, 7.9mg/l and 8.6mg/l respectively. The cations of their solutes are derived from rock dissolution by chemical weathering. Generally, chemical compositions of groundwater are controlled by the underlying geology (Ghadami et al., 2012; Offodile, 2014). Gibbs (1970) demonstrated the assessment of sources of dissolved ions by plotting the water samples in accordance to the variations in the ratio of Na/Na+Ca as function of Log_{10} TDS. The Gibbs plot (Fig. 8) for the PVL springs revealed it is controlled mainly by water-rock interaction processes. The major element abundance order for the springs is in the order of: $Mg^{2+} > Ca^{2+} > Na^{+} > K^{+}$. The major oxide distribution pattern for the PVL volcanic rocks are $MgO > CaO > Na_2O > K_2O$ (Lekmang, 2019). The similarity in the major cations concentration pattern with that of the major oxide is suggestive of derivation from the parent volcanic rocks. Similarities in geochemical distribution in groundwater, soil and parent rock are suggestive of source of derivation (Offodile, 2014; Matinez Cruz, 2008; Lar and Usman, 2012). Generally, silicates of volcanic rock gets weathered by hydrolysis producing Mg-Ca-HCO_3 rich and Na^+ and K^+ bicarbonate depleted groundwater or vice versa depending on the volcanic rock type dominating (Jones et al., 1977; Ghiglierri, 2012). Mg^{2+} and Ca^{2+} are derived mainly from the mineral labradorite to bytonite as the major mineral composition of basalts of the PVL volcanoes (Lar and Gusikit, 2015; Lekmang, 2019). The bicarbonate is derived mainly from the dissolution of the silicate minerals of orthoclase, plagioclase (labradorite), hornblende (Chourasia, 2007; Lar and Gusikit, 2015).

The PVL spring waters plotted on the Piper diagram (Fig. 7) displayed a predominantly Mg-Ca-HCO_3 water type ($\geq$ 80%) and a minor water type constitute cations of Na^+ and K^+ (< 20%). The spring waters falls within the sector 'bicarbonate calcium' and this implies the waters are weakly mineralized. The PVL springs are generally within < 0.1 to 2.5km away from the elevated volcanic cones which are the main recharge areas (Figs. 5, 6).

Stable chemical isotopes of Oxygen ($\delta^{18}O$) and Hydrogen (δ^2H) are used to study and distinguish meteoric water (Craig, 1961), distinguish between shallow and deep water concentrations (Praasma et al., 2009), meteoric and magmatic water zones mixing (Faure, 1996; Martin del Pozzo, 2002). The environmental isotopes of oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$) occur as a result of the fractionation characteristics and are used to determine recharge characteristics to aquifer (Craig, 1961; Chad Basin Commission, 2010). The stable oxygen and hydrogen isotope composition of all the PVL springs are within the range of meteoric water (Craig, 1961; Martin Del Pozzo, 2002; Chad Basin Commission, 2010). This composition is further affirmed by the plot of $\delta^{2}H$-$\delta^{18}O$ and correlation with Standard Meteoric Water Line (Fig. 8). The composition and plot of $\delta^{2}H$ versus $\delta^{18}O$ for the PVL springs reveals three relationships- (1) The Bwonpe and Ampang volcanic springs located in the southeastern extreme of the PVL, (2) Punguk-Amshall-Niyes-Tugwang springs situated in the central and northern extremes of the PVL and (3) Hiktup spring situated in the extreme north and emanating in fractured granite gneiss and has a composition of $-20_{0/00}$ and $-3.6_{0/00}$ for $\delta^{2}H$ and $\delta^{18}O$ respectively. The $\delta^{2}H$-$\delta^{18}O$ of Hiktup spring plots distinctively from other springs (Fig.9). There is a wide compositional variation between the springs within the basaltic and the granitic aquifers. The springs within the basaltic environment are recharge from the high altitude of ≥ 1400masl and the basement within ≤ 1200masl. Isotopic compositional variations have been used to distinguish between different aquifers (Almoni, 1994; Praasma at al., 2009). These results are suggestive of two different aquifers within the Panyam Volcanic Line.

5.3. Groundwater suitability for drinking and irrigation purposes

A comparative hydrochemical value of the PVL springs (Table 2) and WHO drinking water quality standard (WHO, 2004) showed they are all within permissible levels and hence are all potable.

Ground water for irrigation suitability can be based on their pH, TDS, and EC values (Chad Basin Commission, 2010; www.smartfertilizer.com). A pH value of 7 indicates neutral water while lower or higher values correspond to acid or alkaline waters respectively. TDS values of < 1,500mg/l, 1,500-5,000mg/l and > 5000mg/l are classified as fresh water, brackish water and saline respectively (Chad Basin Commission, 2010; Durairaj et al., 2015). Generally, electrical conductivity (EC) of any water is a reflection of the TDS constituent.

One of the main parameter in irrigation water quality and soil management is Sodium Adoption Ratio (SAR). It is an indicator of suitability for water-use in irrigation as determined from the concentration of the cations of Mg^{2+}, Ca^{2+} and Na^{+} present in the water (fao.org). The SAR is calculated from the formular, SAR $\frac{Na^{+}}{\frac{\sqrt{Ca^{++}+Mg^{++}}}{2}}$ (US Salinity Laboratory, 1954; FAO.org.). The calculated SAR for the PVL springs ranged from 1.96 to 3.79 (Table 3) and these values falls within the SAR values of less than 10 and therefore the spring waters are suitable for irrigation use.

The soluble sodium percentage (SSP) is known to be one of the most hazardous in irrigation management practice (US Salinity Laboratory, 1954; Durairaj et al., 2015, FAO.org). The excess of the sodium in water is known as sodium hazard (Durairaj 2015). This has been found to reduce soil permeability through clogging of soil particles (Nagaraju et al., 2012; Durairaj et al., 2015). The soluble sodium percentage is defined by: -SSP = $\frac{Na^{+}+K^{+}}{(Ca^{2+}+Mg^{2+}+Na^{+}+K^{+})} \times 100$ where all concentrations are in mg/l. SSP value of less than 10, falls within solidified hazard class of excellence as per irrigation water use criteria (US Salinity Laboratory, 1954; Durairaj et al., 2015). The calculated SSP value for the PVL springs falls between 26 and 54% and falls within good to permissible class or category of irrigation water. Generally, the spring waters are suitable for irrigation use for different varieties of crops. The predominant irrigated crops along the spring wetlands are sugar cane (saccharum afficinarum), solarium tuberosum and vegetables (carrots, spinach etc).

Table 3. Average Sodium Adoption Ratio (SAR) and Soluble Sodium Percentage (SSP) of PVL springs

Location	SAR	SSP (%)
Bwonpe volcanic spring	0.56	30.52
Ampang spring	0.44	31.13
Punguk spring	0.77	26.47
Amshall spring	0.61	33.87
Niyes spring	0.65	38
Hiktup spring	0.84	54.20
Tugwang spring	0.59	31.18

6. Conclusions

The study established the hydrogeology of the PVL volcanic springs. The springs are mainly recharged from rainfall through the semi permeable and permeable rocks of volcanic ejecta materials forming shallow and deep ground water circulation system and flow out at spring points through fractured/jointed basalts and/or sub-basalt alluviums with short residence time. The major dominant water type is Mg-Ca-HCO_3 type while the minor type are of (Na^+ + K^+)-HCO_3 and are all suitable for drinking and irrigation purposes. The hydrogeochemical constituents derived mainly from water-rock interaction processes. Stable oxygen and hydrogen isotopes composition and of the spring waters show that they are mainly of meteoric origin.

There is need for a continuous hydrochemical monitoring of the springs of the Panyam Volcanic Line as well as the Pidong Crater Lake which is noted for hydrochemical and lake colour changes in recent times. The hydrochemical investigation will give further information on the activity level of the Panyam line volcanoes which were classified as neither extinct nor dormant.

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