Weathering of Meta-Igneous Rocks in Parts of the Basement Terrain of Southwestern Nigeria: Implications on Groundwater Occurrence

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Abstract- Weathering indices of meta-igneous rocks was qualitatively employed to decipher groundwater potentiality in Ekiti-State. Five representative samples of weathered migmatite, granite and charnockite were analysed for major and trace elements using X-Ray Fluorescence Spectrometry Analytical methods. Temperature (^oC), EC (µS/cm), pH and wells static water levels/depths were measured using Multi-parameter TestrTm 35 series Meter and dip meter respectively. Ruxton ratio (RR), Chemical Index of Alteration (CIA), Chemical Index of Weathering (CIW) and Plagioclase Index of Alteration (PIA) were estimated from the chemical data. The weathering indices revealed granitic terrain with average values of RR (3.04), CIA (93.14%), CIW (98.29%) and PIA (98.19%) as the most favourable for groundwater occurrence. Migmatite with average values of RR (3.61), CIA (86.51%), CIW (91.01%) and PIA (90.45%) ranked second while charnockite with mean values of RR (3.30), CIA (84.70%), CIW (88.84%) and PIA (88.25%) was least favourable. The RR values fell in the moderately weathered profile while CIA, CIW and PIA have values greater than >50% which signified intense tropical weathering. This observation agreed with existing boreholes records in the area with average yields of 105.75m^3/day, 70.21m^3/day and 67.16m^3/day in granite, migmatite and charnockitic terrains respectively.

Index Terms- Weathering intensity; meta-igneous rocks; static water levels; weathering indices; borehole yield

I. INTRODUCTION

Weathering is the breakdown and alteration of rocks at earth's surface through physical and chemical reactions with the atmosphere and the hydrosphere. Weathering is a fundamental process in the geological cycle and of equal importance as the processes of metamorphism, volcanism, diagenesis, erosion etc. [1]. Exposed rocks are affected to variable degrees by a combination of chemical and physical weathering [2]. From hydrogeologic point of view, weathering is important because it transforms the solid bedrock into small fragments which constitute aquifers where groundwater resides. Weathered products of the basement complex often form a significant water-bearing layer directly overlying the fresh basement complex rocks [3]. The weathering of rocks is influenced by a number of variables, such as the mineral composition, the texture of the rock, and the climate in which weathering occurs. Differential weathering is a result of differences in the rates of weathering.

This study concentrates on Ekiti basement terrain of southwestern Nigeria, an archean-early proterozoic meta-igneous rocks area that responded differently to weathering and indirectly to groundwater occurrence. Chemical weathering is the breakdown of minerals by chemical reactions with the atmosphere or hydrosphere vides dissolution, hydrolysis, and oxidation. During chemical weathering, rocks are decomposed, the internal structures of the minerals are destroyed and new minerals are created. Thus, there is a significant change in the chemical composition and physical appearance of the rock apart from redistribution of elements in the lithosphere and hydrosphere. In Ekiti basement terrain, groundwater occurrence is erractic, the groundwater in such basement setting requires a quantitative knowledge of hydro-geophysical parameters of the hydrogeologic unit which reveals the superficial materials overlying the crystalline bedrock and the bedrock structures [4]. Several geophysical studies [5, 6, 7, 8, and 9] targeted towards locating aquifers with deep overburden thickness and or fractures have been carried out in the Basement terrain of southwestern Nigeria. [10] Carried out a research work on the influence of bedrock weathering on the shallow ground water system around felsic meta-sediment and amphibolites of the Ilesha schist belt and concluded that the bedrocks had some control on the shallow groundwater of the study area. In most Basement Complex rocks, weathered products, reflect certain characteristics (geochemical and mineralogical) of the parent rock which could be used indirectly as pathfinder to groundwater occurrence and distribution. The present study apart from discussing bedrocks control on groundwater occurrence attempt to validate the groundwater distribution within the rock units using weathering indices of rocks estimated from chemical data of weathered rocks in the study area.

A. Location of Study

The study area lies between latitudes 7^0 15′ - 8^0 5′N and longitudes 4 ^{0} 44′ – 5^0 45′ E. It lies south of Kwara and Kogi States, East of Osun State and bounded by Ondo State in the East and in the south (Fig. 1.). Major towns such as Ado, Ikere, Ise, Ire, Ifaki, Ilawe, Igede, Ijero, Aramoko and Ikogosi have good road network that facilitated geological and hydrogeochemical sampling operations. The study area is in the tropic within the rainforest vegetation. It has two main seasons; the rainy and dry seasons. The wet season covers April-October while the dry season is from November-March. The wet season is controlled mainly by the prevailing south-westerly winds from the Gulf of Guinea while the dry season is as a result of the dry continental northeast wind (Harmattan) that originated from the Sahara desert. The mean annual rainfall and temperature are 1500mm and 28°C respectively. The present climatic situation is changing gradually due to effects of global warming. Field observation revealed that the study area is in a hummocky terrain with a well pronounced undulating topography characterised with prominent hills having steep slope with elevation between 200m and 500m above mean sea level.

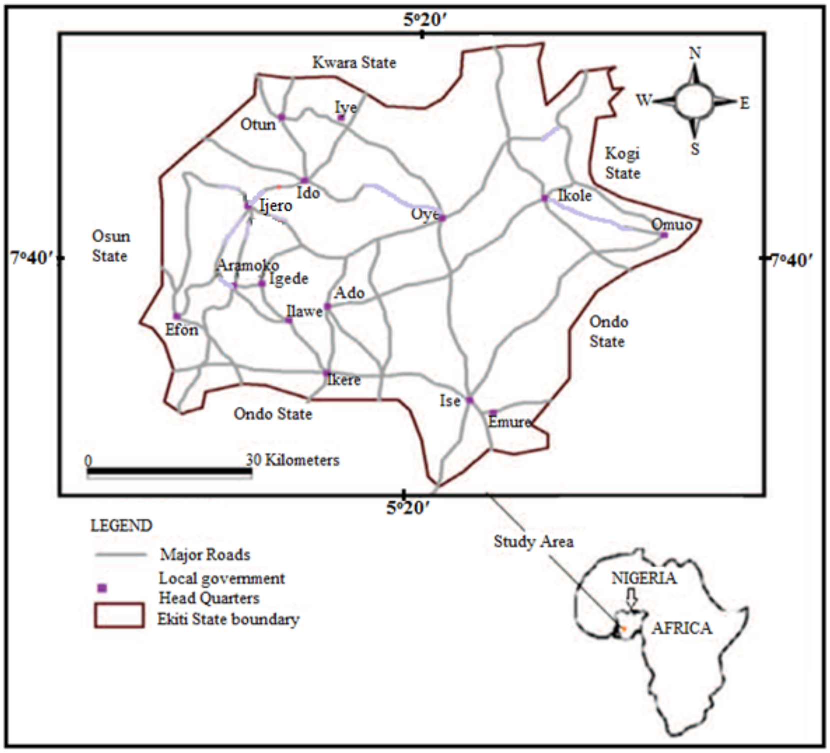

Figure1: Location of study

B. Geology of the study area

The rocks constituting the study area are categorized into three major groups: the migmatite-gneiss complex, the series of approximately north-south trending Proterozoic schist belts and the Pan-African Granites [11]. Over 70% of the study area is covered by the migmatite-gneiss complex comprising of migmatite, migmatite gneiss, banded-gneiss and granite-gneiss rock outcrops. The banded and granite gneisses are mostly biotite and biotite- hornblende gneiss with alternating light and dark bands. The gneisses are low lying outcrop that have suffered poly cyclic metamorphism apart from different episodes of weathering operations (Fig.2). Massive quartzite along with approximately N-S trending psammite intruded into the pre-existing migmatite-gneiss complex while the granites / charnockite were emplaced during the Pan-African orogeny (600±150Ma). Prominent outcrops of granite forming high rising hills are found especially in the Ado, Igede, Iyin and Ikere areas. Charnockite often occur in association with the granites and their distribution are similar to the granitic rocks variedly spread within the study area. Responses of these various categories of rocks to weathering differ and as such a proper understanding of their weathering intensities could serve as a guide to groundwater potential classification in the area.

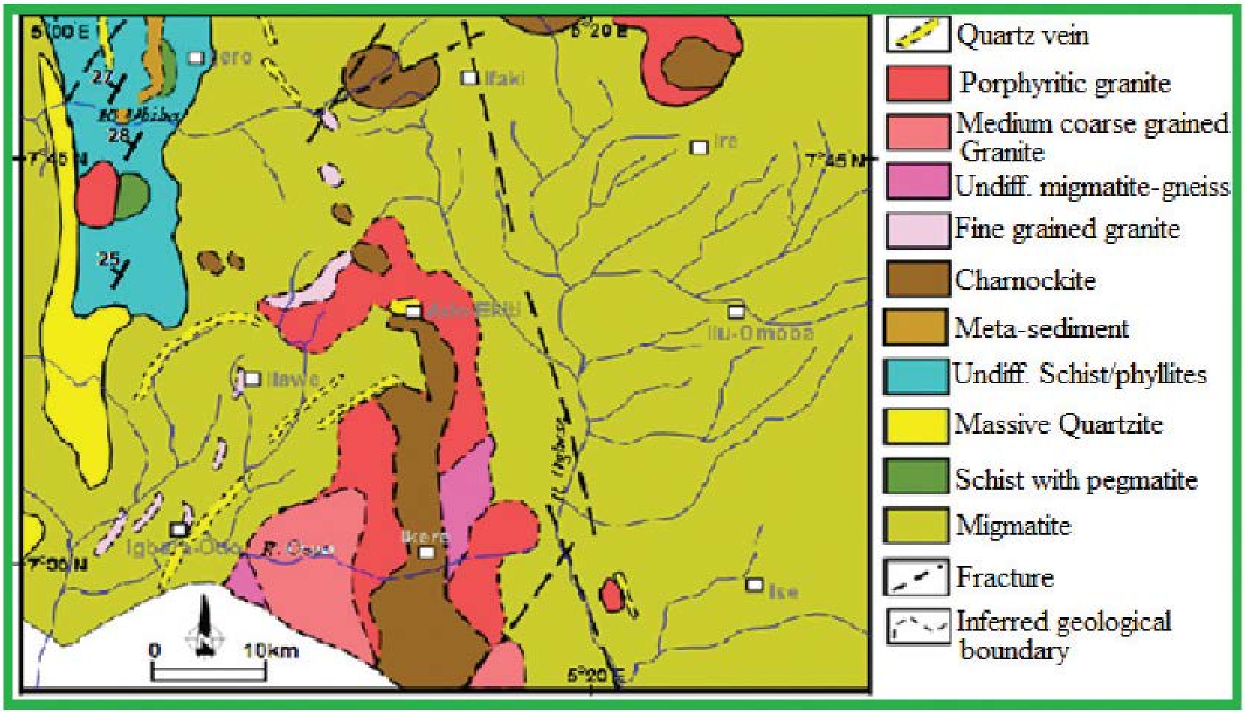

Figure 2: Geologic Map of Study area [12].

II. METHODOLOGY

A reconnaissance survey to the study area was carried out during which the rocks distributions were critically assessed in preparation for field operation.

During the field operations, five samples each of weathered migmatites, granite and charnockite were collected for geochemical analysis. Prior to sampling of weathered rock units, the surface of the weathered samples were removed using shovel or cutlass and the sample collected were put inside cellophane paper and properly labeled. The weathered rock sample was thoroughly washed with deionized water to remove superficial dust. The samples were air dried in the Laboratory and pulverized to powder using agate mortar and pestle. The powder was then passed through mesh of 0.5mm. Sample pellets were kept in sachets of polythene bags, labeled and again kept in poly propylene container ready for analysis. Weathered rock samples already grounded down to forty micron (40µ) were loaded into the X-Ray diffractometer. The X-ray diffraction study uses principles based on X-ray beam moving through the powdered samples. When a sample is measured using XRF, each element present in the sample emits its own unique fluorescent x-ray energy spectrum. By simultaneously measuring the fluorescent x-rays emitted by the different elements in the sample, hand held Thermo Scientific Niton XRF analyzers rapidly determine those elements present in the sample and their relative concentrations in other words, the elemental chemistry of the sample. The weathered rocks were analyzed for elemental composition using the Energy Dispersion X-ray fluorescence (EDXRF) spectrometer at the centre for Energy and Development, Obafemi Awolowo University, Ile-Ife. The geochemical data for the fresh rocks in this study were lifted from [13] to give room for comparative evaluation of the fresh and weathered rock units.

The geochemical data of the weathered rocks were subjected to data evaluation using SPSS17 while the weathering intensities were estimated employing the following weathering indices:

(a) Ruxton Ratio (RR)

(RR) was estimated using RR = SiO_2/Al_2O_3 [14] (1)

(b) Chemical Index of Alteration (CIA)

The CIA of the sampled weatherd rock was computed using

CIA = $100(Al_2O_3/\ (Al_2O_3+CaO+Na_2O_3+K_2O))$ [15]. (2)

(c) Chemical Index of Weathering (CIW)

The Chemical Index of Weathering (CIW) was estimated using

CIW = 100{Al_2O_3/ (Al_2O_3+CaO+Na_2O_3)} [16] (3)

(d) Plagioclase Index of Alteration (PIA)

The PIA in line with the work of [15] was computed using

PIA = 100{(Al_2O_3-K_2O /Al_2O_3+CaO+Na_2O_3-K_2O) (4)

Subsequently, well inventory was embarked upon during which water levels and depths of wells were measured using electronic dip meter while a Multi-parameter TestrTm 35 series Meter was employed for in-situ measurement of temperature, pH and electrical conductivity. The electronic dip meter consists of a graduated tape, usually in meters and feet with a sensor or electrode attached to the lower portion. The sensor (electrode) is lowered into the boreholes and as it touches the water, the electric circuit is completed and a bulb on the cable reel lights up or a whistling noise or beep is activated. The depth to water level is now read out and recorded.

III. RESULTS AND DISCUSSION

A. Geochemical composition of Fresh/Weathered rocks in the study area

The climatic condition of the study area is warm and humid with appreciable rainfall. Thus chemical weathering becomes markedly pronounced and the individual minerals that form the rocks were each subjected to rather intense chemical weathering which obviously is complimented by mild mechanical weathering to form soils through which rain water percolates to form groundwater.

In this study, result of the chemical composition (in mass fractions) of weathered migmatite, granite and charnockite from the study area is presented in Table 1 while that of the fresh rocks component extracted from [13] is in Table 2. In the weathered migmatite, SiO_2 concentrations ranged from 59.15 - 65.28%, Al_2O_3 concentrations from 13.41-24.75% and Fe_2O_3 from 4.3-7.02% (Table 1). In the remaining rock units i.e. weathered granite and charnockite; SiO_2 ranged from 61.25-62.10% and 57.89-61.34% respectively. The Al_2O_3 concentrations in the weathered granite ranged from 18.86-22.22% while in charnockite it ranged from 15.87-21.64%. As for the Fe_2O_3 concentrations, the range was 4.44-6.90%, 7.88-10.98% in granite and charnockite respectively. A critical examination of the chemical compositions of fresh rocks in the study area (Table 2) and weathered rocks (Table 1) revealed three oxides (SiO_2, Al_2O_3 and Fe_2O_3) as the principal chemical constituents making up about 70-75% of the rock units of the area. In addition, the general weathering trend revealed enrichment of Fe_2O_3 in the weathered portion of the bedrock and depletion with respect to the fresh bedrocks. . The Al_2O_3 oxide enrichment show increased concentration in the weathered layer compared to the fresh rock.

Table 1: Chemical composition (in mass fractions) of weathered rocks in the study area

Code Rock Type Migmatite	Locality	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**MnO**	**CaO**	**MgO**	**Na_2O**	**K_2O**	**TiO_2**	**P_2O_5**	**LOI**	**Total**
Mf1	Oye	60.61	24.75	4.30	0.05	0.12	0.20	1.56	0.77	0.24	0.03	7.00	99.63
Mf2	Iworoko	59.15	22.85	4.68	0.02	0.19	0.96	0.16	1.01	0.57	0.02	10.00	99.61
Mf 3	Are	65.28	15.34	6.62	0.98	0.84	0.67	0.74	1.06	1.22	0.18	8.00	100.93
Mf 4	Igbemo	63.49	13.41	7.02	1.12	1.13	0.76	1.01	1.14	0.76	0.52	8.80	99.16
Mf 5	Ogbesse	64.66	16.02	5.58	1.04	1.68	0.81	0.93	1.02	1.10	0.11	7.20	100.15
	Minimm	59.15	13.41	4.3	0.02	0.12	0.2	0.16	0.77	0.24	0.02	7	99.16
	Maximum	65.28	24.75	7.02	1.12	1.68	0.96	1.56	1.14	1.22	0.52	10	100.93
	Average	62.64	18.47	5.64	0.64	0.79	0.68	0.88	1	0.78	0.17	8.2	99.9
	Std. Dev.	2.65	5	1.18	0.56	0.66	0.29	0.5	0.14	0.4	0.21	1.23	0.68
Granite													
Mf1	Oye	62.1	22.22	4.44	0.06	0.01	0.01	0.18	0.98	0.04	0.02	9.80	99.86
Mf2	Iworoko	61.25	20.70	5.40	0.02	0.01	0.4	0.26	1.31	0.01	0.03	10.26	99.65
Mf 3	Are	61.61	18.86	6.85	0.03	0.08	0.23	0.16	1.17	0.02	0.02	10.80	99.83
Mf 4	Igbemo	62.05	20.20	6.11	0.04	0.18	0.27	0.24	1.02	0.03	0.03	10.10	100.27
Mf 5	Ogbesse	61.68	19.86	6.9	0.04	0.12	0.18	0.52	1.23	0.02	0.03	8.46	99.04
	Minimm	61.25	18.86	4.44	0.02	0.01	0.01	0.16	0.31	0.01	0.02	8.46	99.04
	Maximum	62.1	22.22	6.9	0.06	0.18	0.4	1.26	2.17	0.04	0.03	10.26	100.27
	Average	61.74	20.37	5.94	0.04	0.08	0.22	0.47	1.34	0.02	0.03	9.48	99.73
	Std. Dev.	0.35	1.23	1.04	0.01	0.07	0.14	0.46	0.77	0.01	0.01	0.71	0.45
Charnockite													
Mf1	Oye	61.34	16.92	8.64	1.36	1.32	0.94	0.87	0.88	1.08	0.63	5.81	99.79
Mf2	Iworoko	59.42	17.61	8.89	1.83	1.48	0.69	0.89	0.97	0.98	0.54	6.9	100.2
Mf 3	Are	59.61	15.87	10.83	1.96	1.47	0.91	1.01	1.21	1.12	0.47	5.12	99.58
Mf 4	Igbemo	58.67	21.64	7.88	1.01	1.02	0.78	0.9	1.02	0.89	0.5	5.01	99.32
Mf 5	Ogbesse	57.89	18.98	10.98	0.98	1.28	0.81	1.02	0.89	1.02	0.48	5.21	99.54
	Minimm	57.89	15.87	7.88	0.98	1.02	0.69	0.87	0.88	0.89	0.47	5.01	99.32
	Maximum	61.34	21.64	10.98	1.96	1.48	0.94	1.02	1.21	1.12	0.63	6.9	100.2
	Average	59.39	18.2	9.44	1.43	1.31	0.83	0.94	0.99	1.02	0.52	5.61	99.69
	Std. Dev.	1.29	2.23	1.39	0.45	0.19	0.1	0.07	0.13	0.09	0.07	0.78	0.33

Table 2: Chemical composition (in mass fractions) of Fresh rocks in the study area [13]

Code Rock Type Migmatite	Locality	SiO_2	Al_2O_3	Fe_2O_3	MnO	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	LOI	Total
Mf1	Oye	69.80	15.46	2.50	0.20	2.40	0.43	3.30	3.58	0.08	0.04	2.01	99.80
Mf2	Iworoko	69.40	15.18	2.70	0.34	1.86	0.24	3.80	4.04	0.09	0.06	2.21	99.92
Mf 3	Are	68.40	14.98	2.13	0.38	2.12	0.36	4.46	4.51	0.10	0.05	2.35	99.84
Mf 4	Igbemo	66.50	15.22	3.13	0.26	2.10	0.48	4.34	4.32	0.07	0.04	3.32	99.78
Mf 5	Ogbesse	69.00	14.65	3.46	0.40	3.03	0.31	3.52	3.76	0.06	0.05	2.02	100.30
	Minimm	66.50	14.65	2.13	0.20	1.86	0.24	3.30	3.58	0.06	0.04	2.01	
	Maximum	69.80	15.46	3.46	0.40	3.03	0.48	4.46	4.51	0.10	0.06	3.32	
	Average	68.60	15.10	2.78	0.32	2.30	0.36	3.88	4.04	0.08	0.05	2.38	
	Std. Dev.	1.29	0.30	0.52	0.08	0.45	0.10	0.51	0.38	0.02	0.01	0.54	
Granite													
Mf1	Oye	75.00	15.24	2.44	0.09	0.98	0.09	1.57	2.49	0.03	0.23	2.15	100.33
Mf2	Iworoko	72.10	14.98	2.37	0.12	1.01	0.12	1.21	4.02	0.05	0.15	2.05	98.13
Mf 3	Are	74.00	15.68	2.19	0.10	0.91	0.08	1.48	3.47	0.02	0.03	2.04	100.03
Mf 4	Igbemo	71.89	15.10	2.26	0.08	0.86	0.13	1.88	3.64	0.04	0.11	2.16	98.15
Mf 5	Ogbesse	73.56	15.22	2.43	0.11	0.82	0.20	1.75	3.19	0.06	0.01	2.28	99.63
	Minimm	71.89	14.98	2.19	0.08	0.82	0.08	1.21	2.49	0.02	0.01	2.04	
	Maximum	75.00	15.68	2.44	0.12	1.01	0.20	1.88	4.02	0.06	0.23	2.28	
	Average	73.30	15.24	2.34	0.10	0.92	0.12	1.58	3.36	0.04	0.11	2.14	
	Std. Dev.	1.33	0.27	0.11	0.02	0.08	0.05	0.26	0.57	0.02	0.09	0.10	
Charnockite													
Mf1	Oye	66.10	12.58	2.81	0.10	4.22	4.11	3.05	2.46	1.13	0.61	2.80	99.95
Mf2	Iworoko	65.20	10.22	3.02	0.21	4.30	3.03	3.45	3.14	1.01	0.56	3.55	97.70
Mf 3	Are	65.40	12.36	4.16	0.17	4.98	2.67	2.78	3.36	1.10	0.67	2.55	100.20
Mf 4	Igbemo	66.89	11.85	3.64	0.15	3.22	1.89	3.13	2.47	0.98	0.71	2.82	97.75
Mf 5	Ogbesse	67.77	13.03	3.08	0.14	3.18	1.94	3.29	2.98	1.04	0.53	3.18	100.20
	Minimm	65.20	10.22	2.81	0.10	3.18	1.89	2.78	2.46	0.98	0.53	2.55	
	Maximum	67.80	13.03	4.16	0.21	4.98	4.11	3.45	3.36	1.13	0.71	3.55	
	Average	66.30	12.01	3.34	0.15	3.98	2.73	3.14	2.88	1.05	0.62	2.98	
	Std. Dev.	1.07	1.09	0.55	0.04	0.77	0.91	0.25	0.40	0.06	0.07	0.39	

Furthermore the cross plot of SiO_2 against Loss of Ignition (LOI) (Fig. 3) revealed that the three rock units (migmatite, charnockite and granite) defined a clear trend between weathered and fresh rock units.The fresh rock samples are rich in SiO_2 compared to the weathered samples. However, LOI is high in the weathered rock units indicating the influence of weathering processes through the depletion of silica and enrichment of Fe, Al and water with increasing weathering. These chemical components are leached during rainfall into the groundwater system of the study area. The high concentrations of Fe_2O_3 in charnockite (Fig. 4) gave erroneous belief of possible enrichment of iron in groundwater within charnockitic bedrock compared to migmatite and granitic terrain. Moreover, as water depletion occurred in the rock the weathering intensity increased more around the migmatite and granite than the charnockite. A plot of SiO_2 against Fe_2O_3 (Fig 5.) revealed that charnockite is more enriched in Fe_2O_3 in the weathered samples compared to migmatite and granite that are at parity, implying that charnockite is rich in Fe bearing minerals which are leached out into groundwater during chemical weathering. However, this difference was not explicit as indicated by [13] where chemical compositions of iron in groundwater in magmatic, granitic and charnockitic bedrocks of the area ranged from 30-3050µg/L, 20-4330µg/L and 40-620µg/L respectively. Occurrence and distribution of iron in groundwater is controlled by the amount of oxygen in the water and to a lesser extent, its degree of acidity, i.e., its pH. Iron can occur in two forms: as Fe^{2+} and as Fe^{3+}. At high levels of dissolved oxygen in groundwater iron occurs as Fe^{3+} while at lower dissolved oxygen levels, the iron occurs as Fe^{2+}. Groundwater that is poor in oxygen encourages iron dissolution readily especially if the pH of the water is on the low side (slightly more acidic). Thus the low concentrations of iron in the groundwater of the study area is as a result of the chemical behaviour of iron and its solubility in water which depends strongly on the oxidation intensity in the system in which it occurs [17] as well as its pH [18] being a transition element with a specific stable range of pH – Eh in aqueous solution, is controlled by the redox condition of groundwater.

B. Weathering Intensity

Quantitative estimations of weathering (weathering intensities) in rocks are easily achieved by using whole rock geochemical data to calculate geochemical weathering proxies which make use of the changes of bulk rock geochemical composition caused by chemical alteration. A very simple proxy is the Ruxton Ratio RR [13] given by the SiO_2/Al_2O_3 ratio. The RR ratio assumed that Al_2O_3 remains immobile during weathering so that changes in RR reflect silica loss as a proxy for total element loss [19]. A comprehensive review of a great number of geochemical weathering indices was presented by [19].

However, in this study RR, CIW, CIA and PIA were estimated and their results are as presented in Table 3. The results indicated RR of 2.45-4.73 (av. 3.61), 2.79-3.27(av. 3.04) and 2.71-3.27(av. 3.04) for weathered migmatite, granite and charnockite respectively. Also, in the same rock units, CIA ranged from 80.35-94.38 (av. 86.51), 88.67-95.00 (av.91.44), and 81.13-95.00 (av.91.44), while CIW ranged from 85.99-98.49 (av. 91.01), 94.22-99.15 (av. 97.39) and 86.49-99.13 (av. 97.39). However, the PIA ranges from 96.76-107.53 (av 101.62), 97.00-124.22 (av.111.68) and 97.45-124.22 (av. 111.68) respectively (Fig. 6). The difference between the CIA, PIA and CIW is that potassium oxide (K_2O) was subtracted from PIA and was added in case of CIA while in the CIW it was not included in the equation. Ruxton Ratio values<2.9 suggested high degree of weathering. In this study, most of the RR values were greater than 2.9 and fell in the moderately weathered profile. However, the estimated indices for CIA and CIW have values greater than >50% which is the optimum weathering value for fresh unweathered upper crust materials. As regards the weathering rate of plagioclase feldspar PIA with optimum weathering values>100%, similar weathering pattern to CIW and CIA was exhibited. These high values were indications of the fact that primary materials present in the rock must have been subjected to substantially moderate to high degree of weathering and reworking of ferromagnesian minerals and feldspars which subsequently dissolved and leached into the surrounding groundwater system. Furthermore, correlation plots of % CIA vs % Al_2O_3 (Fig. 7) and % CIW vs % LOI (Fig. 8) further buttress differential weathering with a correlation value of (r = 0.91, 0.90) for the migmatite and granite while that of charnockite is a higher correlation value of (0.94). Also, from Fig.8 CIW cross plot against LOI gave a correlation of r = 0.48, 0.21, 0.28 for the migmatite, granite and charnockite respectively. From Fig. 8, granite is observed to have the highest water loss with increasing weathering followed by migmatite and charnockite respectively. Likewise, the rate of alumina depletion followed similar pattern with the general weathering trend (Fig.7). In both Figs. 7 and 8, samples from granite and charnockite have a clearly defined trend as against those from migmatite. This observation is a reflection of the petrogenesis of migmatite. However, differential weathering as observed in the three rock units are as a result of combination of factors such as variation in mineral composition, textural characteristics and climate.

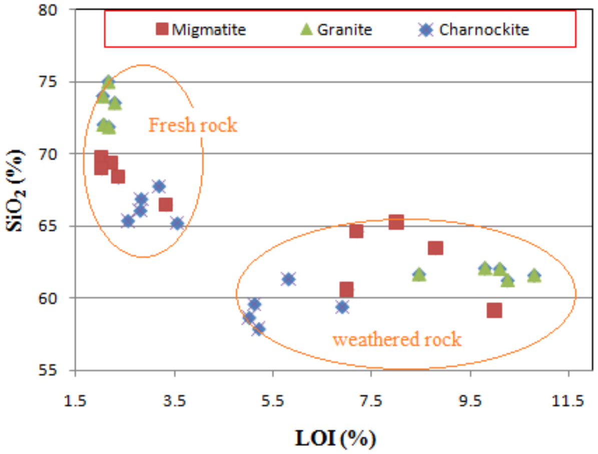

Figure 3: Cross plot of SiO_2 against LOI.

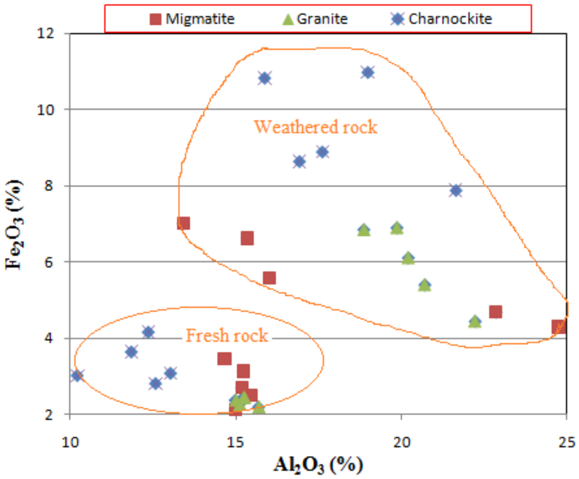

Figure. 4: Cross plot of Fe_2O_3 against Al_2O_3.

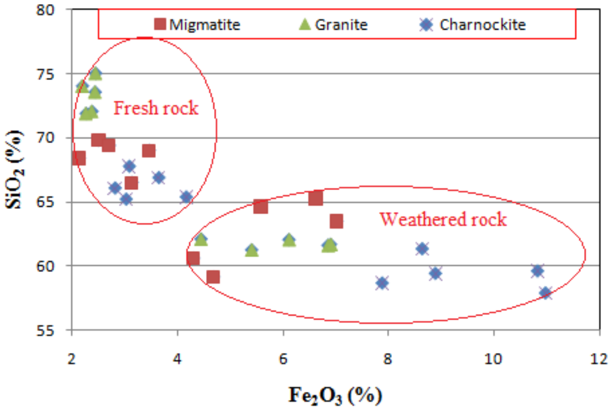

Figure 5: Cross plot of of SiO_2 against Fe_2O_3.

Table 3: Weathering indices of rocks in the study area.

Rock Type	RR	CIA	CIW	PIA
Migmatite	2.45	90.99	93.64	93.45
	2.59	94.38	98.49	98.42
	4.26	85.32	90.66	90.04
	4.73	80.35	86.24	85.15
	4.04	81.53	85.99	85.18
Min	2.45	80.35	85.99	85.15
Max	4.73	94.38	98.49	98.42
Mean	3.61	86.51	91.01	90.45
STDEV	1.03	6.05	5.27	5.67
Granite	2.79	95.00	99.15	99.11
	2.96	92.91	98.71	98.63
	3.27	93.04	98.74	98.66
	3.07	93.35	97.96	97.86
	3.11	91.39	96.88	96.68
Min	2.79	91.39	96.88	96.68
Max	3.27	95.00	99.15	99.11
Mean	3.04	93.14	98.29	98.19
STDEV	0.18	1.28	0.90	0.96
Charnockite	3.63	84.64	88.54	87.99
	3.37	84.06	88.14	87.53
	3.76	81.13	86.49	85.53
	2.71	88.04	91.85	91.48
	3.05	85.61	89.19	88.72
Min	2.71	81.13	86.49	85.53
Max	3.76	88.04	91.85	91.48
Mean	3.30	84.70	88.84	88.25
STDEV	0.43	2.51	1.96	2.16

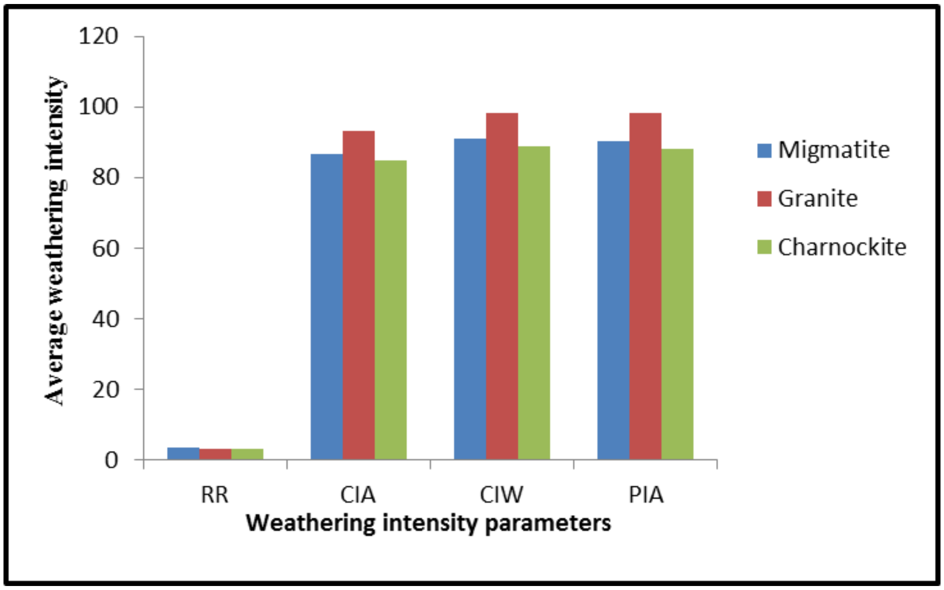

Figure 6: Average weathering intensity based on rock units.

In the study area climatic factor is fairly uniform but rainfall distribution is variable which affects response of the rocks to weathering. Mineral composition is of primary importance in the weathering of the rocks in the study area. Quartz is very stable and remains essentially unaltered for long periods of time. Other minerals such as olivine and plagioclase feldspar decompose almost immediately as they are not thermodynamically at equilibrium with their new surface environment. The differences in granite and charnockite trends are not only controlled by mineralogy but by the differences in texture of the rocks. Greater proportions of granitic rocks in the study area are of porphyritic texture while the charnockites are fine grained. Thus the porosity and permeability which govern the ease with which water can enter the rocks and attack the mineral grains are more favourable in the granites which resulted in high LOI (Fig.8). Definitely, the weathering trends potray granite to be more favourable for groundwater occurrence. The results obtained and deductions from the weathering intensities were validated using the physical data obtained in this research as shown in Table 4. The statistical summary of the physical data as presented in Table 5 revealed that the average temperature in migmatite was 26.86, 26.52 in granite while it was 26.80 in charnockite. Thus the effects of temperature on the weathering of rocks in the study area were fairly uniform. The pH values ranging from 6.00 – 7.80 in the three rock units indicated slight acidity to neutral water and as such the pH effects on the weathering of rocks in the area were equally fairly uniform. Other parameters; EC, TDS and TH indicated low mineralized water, low residence time. In addition, well depths ranged from 1.5 to 13.48 signifying shallow wells. However, water column on granite terrain has maximum value of 7.7m compared to migmatite and charnockite with 6.5m and 4.2m respectively. This observation confirms that granite are more easily weathered than the other rock units and as such constitute better source rock for groundwater occurrence.

Figure 9 revealed two types of wells; the shallow wells (depth<10m) and the relatively deep wells (depth>10m). The depth of wells has no control on the volume of water. However, about 87% of the wells sunk on granite terrain fell in the shallow well category though with variable volume of water while only about 46% wells from charnockite were represented in the shallow water group while majority were in the deep wells category. This observation revealed that groundwater occurrence in charnockitic terrain was low compared with either granite or migmatite terrain. Without doubt, there were other controlling factors including fractures that controlled groundwater occurrence but it can be said that granite terrain appeared more promising for groundwater occurrence compared to migmatite while the charnockitic terrain was worst off.

Further validation of the effects of weathering of meta-igneous rocks on groundwater occurrence in the study area was embarked upon using borehole records extracted from the research of [20] as presented in Table 6. The statistical summary of borehole records in the study area (Table 7) revealed average borehole yields of 105.75m^3/day, 70.21m^3/day and 67.16m^3/day on granite, migmatite, and charnockitic terrains respectively. This average boreholes yield reflect the weathering intensity of the rocks units in the study area with granite having lower RR, higher CIA, CIW and PIA compared to migmatite and charnockite (Fig. 10). Thus the weathering intensities of meta-igneous rocks in the study area can be qualitatively employed to characterize groundwater occurrence with granite more promising than the other rocks (migmatite and charnockite). However, this assertion could be with exceptions as indicated in Table 7 where maximum yield of 354.24m^3/day occurred in migmatite terrain compared to that of granite with maximum yield of 191.81m^3/day. This observation is in line with the work of [21] where in a particular settlement in the study area (Ikere), subsurface fractures have been mapped using geoelectrical techiniques and confirmed by drilling at 22m depth on a charnockitic bedrock where an artesian borehole with estimated yield of 38.6m^3/hr (926.4m^3/day) was intercepted. The existence of fractures and faults in basement terrain improve substantially the yield of boreholes [21].

IV. CONCLUSION

This study revealed SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, K_2O, TiO_2, P_2O_5 and MnO as major oxides composition of the analysed fresh and weathered rocks in the study area. Three oxides (SiO_2, Al_2O_3 and Fe_2O_3) constitute about 70-75% of the fresh and weathered rocks of the study area. The chemical values show a general weathering trend, where Fe_2O_3 is enriched at the weathered portion of the bedrock and depleted around the fresh rock. The Al_2O_3 oxide enrichment reveal increase in concentration in the weathered layer compared to the fresh rock. The general weathering pattern in the study area indicated removal of most alkali (Na and K) and alkaline earth (Ca and Mg) into solution by weathering reactions. Weathering and ferrugenization process result in the removal of ferromagnesian minerals and feldspars through reworking and leaching from the effect of infiltrating rain water.

Weathering intensity especially (CIW, CIA and PIA) signified intense tropical weathering with weathering intensity in the major rock units in the order of Granite >Migmatite>Charnockite.

Validation of weathering of meta-igneous rocks to characterize groundwater occurrence using well data obtained during this study and existing boreholes data in the study area confirmed that granite terrain is more favourable for groundwater occurrence. However, any of the three rocks could be favourable if fractured.

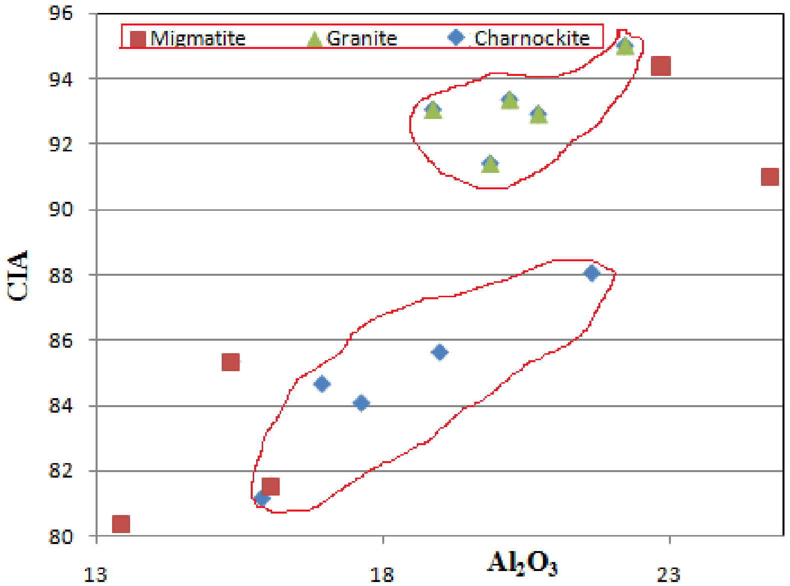

Figure 7: Cross plot of CIA vs Al_2O3 modified after (Tijani et al., 2010).

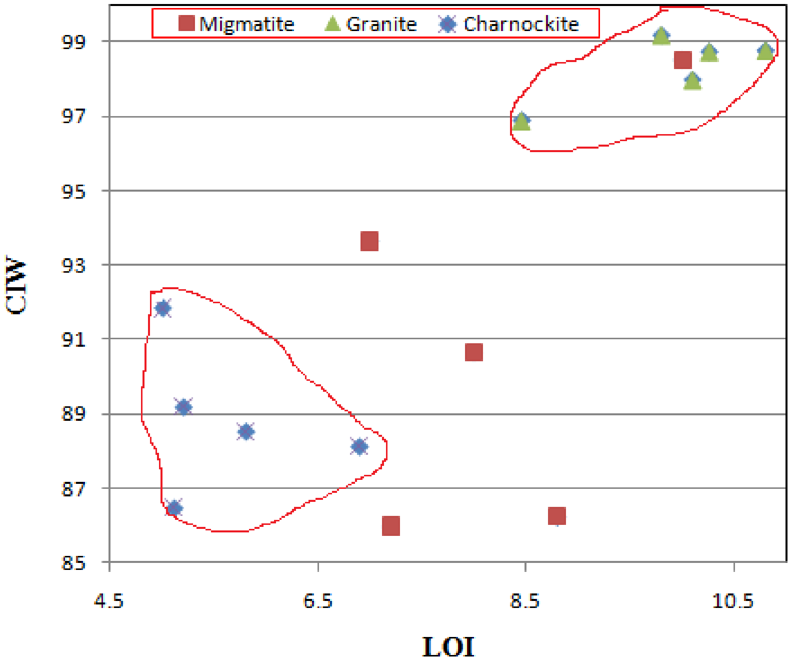

Figure 8: Cross plot of CIW vs LOI modified after (Tijani et al., 2010).

Table 4: Parameters measured in-situ in the study area.

Code	Location	Temp.°C	pH	EC (µS/cm)	TDS (mg/L)	TH	Water Level (m)	Depth (m)	Water column (m)
M2	Aye	26	6	30	22.5	10.53	3.2	9.7	6.5
M3	Ifaki	25.8	6.2	483	362.25	66.23	7.4	13.4	6
M4	Ayegbaju	27.2	7.1	845	633.75	214.8	11.5	13	1.5
M5	Oye	27.6	6.6	195	146.25	71.43	10.5	12.5	2
M6	Igbodo	26.7	6.2	43	32.25	13.53	3.9	6.1	2.2
M7	Eyio	26.4	6.8	683	512.25	155.9	9.7	11.5	1l.80

M8	Olora-farm	26.6	6	143	107.25	24.65	1.2	4.4	3.2
M9	Are	27.4	6.5	554	415.5	127	1.5	6.4	4.9
M10	Araromi-iyin	26.2	6.1	127	95.25	25.2	8.3	8.6	0.3
M11	Ilokun	26.3	6.1	242	181.5	67.83	7	10.2	3.2
M12	Igbemo	27.7	6.7	662	496.5	174.7	4.3	6.7	2.4
M13	Abaegbira-elemi	26.1	6.9	223	167.25	85.09	5.2	5.3	0.1
M14	Bolorunduro	28.5	6.2	656	492	160.8	5.3	5.8	0.5
M15	Ilumoba	27.5	6.2	170	127.5	46.43	2.3	5.4	3.1
M16	Erifun	26.5	6.4	980	735	222.1	2	3.8	1.8
M17	Agoologunja	26.6	6.1	555	416.25	127.2	2.3	6.8	4.5
M18	Abaoyan	27.2	6.1	778	583.5	241.3	6.4	8.2	1.8
M19	Ilupeju-ijan	27.9	6.2	783	587.25	126.2	5.3	7	1.7
M20	Abaefon	24.6	6.1	182	136.5	70.6	2.7	6.9	4.2
M21	Kajola-ise	27.5	6.2	753	564.75	128.3	3	4.7	1.7
M22	Igbaraodo	27.7	6.6	507	380.25	185.1	3.5	6.7	3.2
M23	Okoisa	27.2	6.1	107	80.25	34.38	4.55	7.5	2.95
M24	Abapopoola	26.8	7.1	490	367.5	126	1.3	5.5	4.2
M25	Ogbese	27.6	6.8	634	475.5	117.1	1.3	4.3	3
M26	Ogbese	26.6	6	73	54.75	19.2	1.5	4.5	3
M27	Obada-ise	26.9	6.3	104	78	10.19	8	4.2	0.2
M28	Ise	26.7	6	135	101.25	39.56	3.3	5.5	2.2
M29	Ise	27.6	6.4	962	721.5	259.3	3.7	6	2.3
M30	Orun	26	6.5	612	458	105.9	1.3	4.6	3.3
M31	Orun	27	7.4	437	327.75	66.11	2	5.6	3.6
M32	Abaegbira	26.7	6.1	486	364.5	105.9	3.7	4.6	0.9
G1	Itapa	26.8	6.6	598	448.5	164.6	11	11.5	0.5
G2	Oshin	27.6	6.2	184	138	64.53	11.3	12.6	1.3
G3	Ado	25.8	6.2	90	67.5	9.37	6	7.2	1.2
G4	Ado	25.8	6.1	775	581.25	155.9	5.9	6.2	0.3
G5	Ikere	27.4	6.2	480	360	62.84	2.8	4.1	1.3
G6	Ikere	26.9	6	452	339	58.7	3	4.7	1.7
G7	Ikere	27	6.2	112	84	29.58	6.6	7.8	1.2
G8	Eruobodo	26.3	6	498	373.5	112	2.1	5.2	3.1
G9	Eruobodo	26.4	6.7	244	183	89.37	1.5	9.2	7.7
G10	Ikere	28.1	6.1	161	120.75	20.79	3.6	5.1	1.5
G11	Ikere	26.8	6.2	165	123.75	47.23	7	7.2	0.2
G12	Ikere	27.3	6.8	104	78	12.74	4.5	5.5	1
G13	Ikere	29.9	6.2	254	190.5	83.66	4.7	5.9	1.2
G14	Ikere	27.8	6.2	109	81.75	39.63	1.4	6	5.1
G15	Epe	26.6	6.2	54	40.5	18.16	1.4	6	5.1
G16	Osi	25.3	6.3	180	135	46.24	0	5.6	5.6
G17	Araromi-iyin	27.1	7.5	745	558.75	168.4	4.2	5.4	1.2
G18	Ara-ijero	25.8	6	203	152.25	71.44	1.5	6.2	4.7
G19	Iropora	25.5	7.2	810	607.5	206.8	2.4	4	1.6
FG20	Igede	26.5	6.2	698	523.5	189.9	1	2.7	1.7

G21	Iyin	25.1	6.2	184	138	84	10.3	11.3	1
G22	Igede	23.9	6.5	284	213	87.5	0.2	1.6	1.4
G23	Iyin	24.2	6.1	487	365.25	112.1	9.7	11.3	1.6
G24	Odo	26.4	6	114	85.5	27.38	6.4	7.4	1
G25	Ilawe	27.1	6.3	307	230.25	98.71	10	11.1	1.1
G26	Ijelu	25.7	6.5	638	478.5	161.4	1.9	3.8	1.9
G27	Ilawe	26	7.2	906	679.5	229.2	0.5	1.5	1
G28	Temidire-asa	26.9	6.2	199	149.25	34.12	3.5	4.5	1
G29	Aba-Alawaye	26.7	7.2	373	279.75	144.4	6.2	9	2.8
G30	Aba-Oshun	27	6.1	232	174	51.59	8	9	1
C1	Ilupeju	27.6	6.4	238	178.5	65.95	4.9	7.2	1.3
C2	Ire	26.3	6.2	137	102.75	43.46	0.5	2.5	2
C3	Ire	26.4	6.1	226	169.5	32.61	1.8	3	1.2
C4	Afao	27.8	7	681	510.75	215.1	8	9	1
C5	Ajebandele	25.4	6.1	220	165	57.74	11	11.5	0.5
C6	Ajebandele	26	6.2	98	73.5	12.71	8	10.5	2.5
C7	Fagbohun	26	6.9	314	235.5	119	11	14	3
C8	Obe	26.9	6.4	62	46.5	21.4	2.7	6.9	4.2
C9	Ikere	26.5	6	79	59.25	23.77	9.4	12.1	2.7
C10	Ikere	26.4	7	644	483	61.8	0.5	2.5	2
C11	Ikere	28.1	6.1	180	135	21.11	6.2	8	1.8
C12	Ikere	29.1	6.2	78	58.5	3.22	4.9	5.9	1
C13	Igbole	25.9	6	139	104.25	49.87	10.5	13.7	3.2

Table 5: Summary statistics of parameters measured in-situ in the study area.

Rock Type	Parameters	Temp. ^{o}C	pH	EC (µS/cm)	TDS (mg/L)	TH	Water Level (m)	Well Depth (M)	Water column (m)
Migmatite	Min	24.60	6.00	30.00	22.50	10.19	1.20	3.80	0.10
	Max	28.50	7.40	980.00	735.00	259.30	11.50	13.40	6.50
	Mean	26.87	6.39	439.81	329.82	104.15	4.42	6.95	2.68
	Stdev	0.77	0.38	292.49	219.35	71.63	2.90	2.71	1.59
Granite	Min	23.90	6.00	54.00	40.50	9.37	0.00	1.50	0.20
	Max	29.90	7.50	906.00	679.50	229.20	11.30	12.60	7.70
	Mean	26.52	6.38	354.67	266.00	89.41	4.62	6.62	2.03
	Stdev	1.16	0.41	250.23	187.68	62.09	3.43	2.94	1.80
Charnockite	Min	25.40	6.00	62.00	46.50	3.22	0.50	2.50	0.50
	Max	29.10	7.00	681.00	510.75	215.10	11.00	14.00	4.20
	Mean	26.80	6.35	238.15	178.62	55.98	6.11	8.22	2.03
	Stdev	1.05	0.37	202.52	151.89	56.47	3.89	4.04	1.06

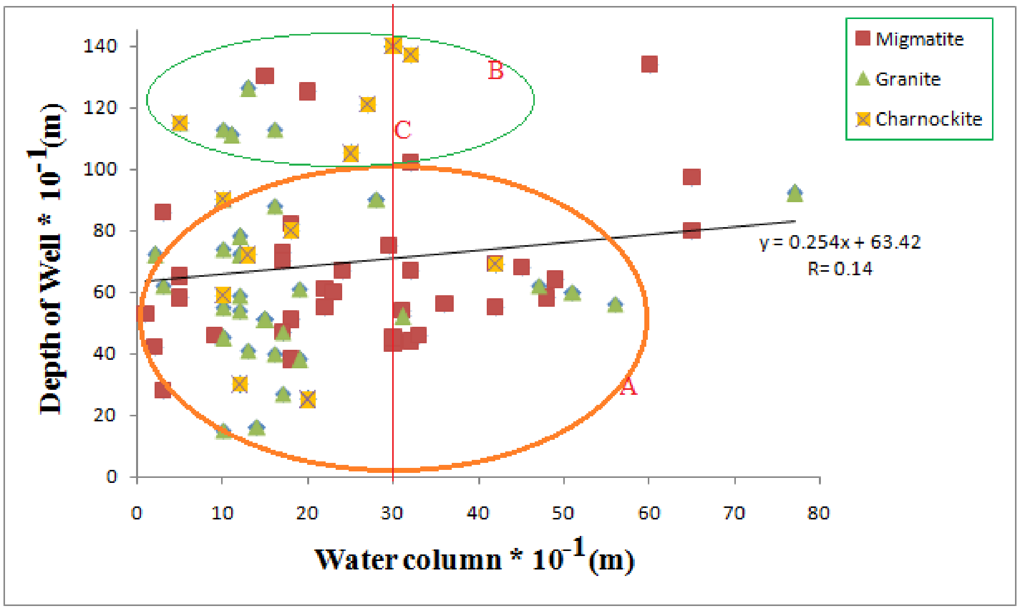

Figure 9: Well deth vs. water clumn

Table 6: Summary of Borehole completion records in Ekiti Basement area [20].

S/NO	Location	BHD/m	SWL/m	Yield (m3/d)	Bedrock
1	Ogbesse	45	4.1	86.4	migmatite
2	Ikere (Ogoga palace)	53	8.9	103.68	granite
3	Ikere(Benin/Owena office)	40	3.9	103.68	charnockite
4	Emure(Owode)	35	1	103.68	granite gneiss
5	Emure(Awopegba house)	30	5.7	69.12	granite gneiss
6	Ise(oraye)	45	4.8	103.68	migmatite
7	Orun	40	4.5	69.12	migmatite
8	Ado(Bolorunduro)	36	3.9	86.4	charnockite
9	Ado(Italaoro)	30	3.3	86.4	granite
10	Igede	35	8	69.12	granite
11	Temidire	43.8	6	131.33	granite
12	Ilumoba	45	7	354.24	migmatite
13	Ago-Aduloju	29.6	2.7	129.6	charnockite
14	Bolorunduro	31.3	3.2	30.24	charnockite
15	Ado-Com. School	40	6.8	132.19	granite
16	Aro Camp-Ikere	42	3.2	54.43	charnockite
17	ESGSC-Ikere	68	18	203.04	charnockite
18	Ado grammar school	51.4	7.2	25.92	granite
19	Ogbese	48.6	1.5	283.39	migmatite
21	Ikoro	60	9	112.32	migmatite
22	Egbewa	50	21	103.68	migmatite
23	Owode	43	2.1	175.39	granite gneiss
24	Ilupo	26	4	103.68	granite gneiss
27	Aramoko-Ekiti	48	14.61	160.7	granite gneiss

28	Ogotun-Ekiti	92	2	129.6	granite
29	Iloro-Temidire	38	9.1	95.04	granite
30	Soso	31.4	8.7	98.49	granite
32	Ado-Ekiti	74	2.7	191.81	granite gneiss
33	Ifaki	40	18	69.12	migmatite
35	Ipoti	50	1.7	53.57	migmatite
36	Epe	31	12	69.12	migmatite
37	Are	40	4.6	34.56	migmatite
38	Iworoko	42	5	43.2	migmatite
39	Ipoti	50	11.8	51.84	migmatite
41	Igede-Ekiti	72	1.3	114.91	granite
42	Orin farm settlement	60	12.4	8.64	charnockite
43	Aba Igbira	37.8	13.9	17.28	migmatite
44	MGHS Ifaki	59	1	86.4	migmatite
45	Ofale community	50	11	11.23	migmatite
46	Ipao CHC	25.5	2.9	21.6	migmatite
47	Eda-Ile	54.7	12.3	31.1	migmatite
48	Ilasa	46.6	6.2	27.65	migmatite
49	Kajola	30	7.2	17.28	migmatite
50	Ipole Iloro	43.5	9.2	11.23	migmatite
51	Ipoti-Ekiti	72	13.97	95.9	granite
52	Igede-Ekiti	72	1.33	114.91	granite
53	Otun-Ekiti	72	3.89	102.81	migmatite
55	Usi-Ekiti	80	10.63	64.8	charnockite
56	Iyin-Ekiti	72	9.15	26.78	granite
57	Ilogbo-Ekiti	70	4.85	44.06	migmatite
58	Iworoko-Ekiti	78	3.5	120.09	migmatite
59	Ire-Ekiti	74	12.8	28.512	migmatite
60	Ijan-Ekiti	70	1.9	40.61	charnockite
61	Igogo-Ekiti	46	1.33	40.61	migmatite
62	Usi-Ekiti	80	10.63	64.8	migmatite
63	Ajebandele	41.5	3	17.28	migmatite
64	Ikogosi	42	14.4	103.68	quartzite
65	Irare Fulani	46.1	NN	36.29	migmatite
66	Irare community	48.4	6.1	8.64	migmatite
67	Ogunnire School	29	8.5	8.64	charnockite
68	Obalatan	50.6	4.5	8.64	charnockite
69	EKSC Ayede	23.4	2.1	21.6	migmatite

Table 7: Statistical summary of Borehole completion records in the study area (20)

Bedrock	Parameter	BHD/m	SWL/m	Yield (m3/d)	Bedrock
Migmatite	Min	23.40	1.00	8.64	Migmatite
	Max	80.00	21.00	354.24	
	Mean	48.90	7.23	70.21	
	Stdev	14.52	5.09	75.97	

Granite	Min	26.00	1.00	25.92	Granite
	Max	92.00	14.61	191.81	
	Mean	52.38	6.10	105.75	
	Stdev	20.78	4.09	42.11	
Charnockite	Min	29.00	1.90	8.64	Charnockite
	Max	80.00	18.00	203.04	
	Mean	48.77	6.62	67.16	
	Stdev	18.10	5.13	60.48	

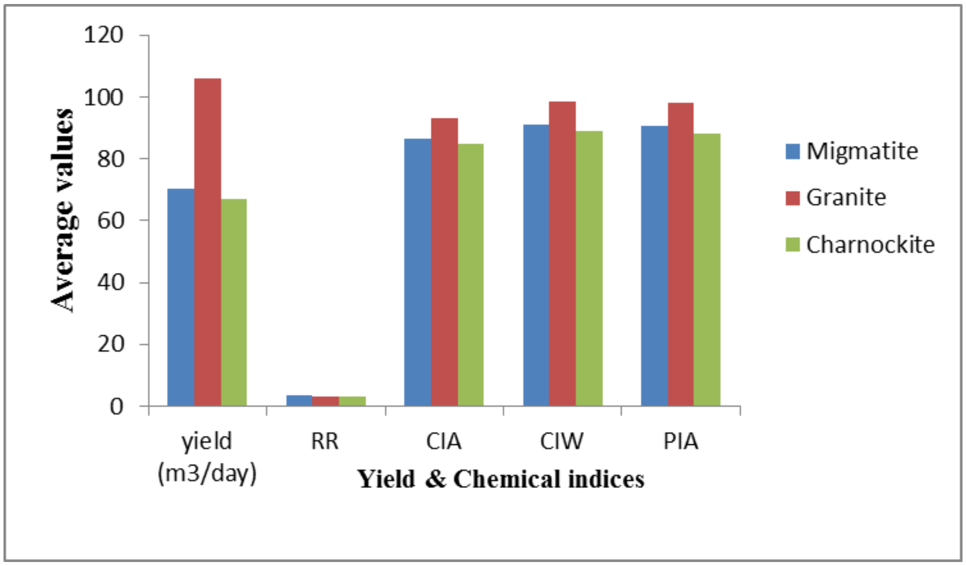

Figure 10: Comparison of average values of boreholes yield and chemical indices based on rock units

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