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Compositional Variations among Gem Tourmalines from Oro, South-western Nigeria

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ABSTRACT

This study investigates the compositional variations of gem-quality tourmalines from two localities in Oro, southwestern Nigeria—Ijomu-Oro and Okerimi-Oro—in order to characterize their geochemical signatures and infer the petrogenetic processes that influenced their formation. Ten samples, five from each site, were analysed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to determine their major, trace, and rare earth element compositions. The results show that all tourmalines are aluminosilicates, consistently enriched in Si and Al, with variable Fe content that correlates with colour intensity, confirming Fe as the dominant chromophore. While samples from the same locality exhibited narrow compositional ranges, those from different sites revealed notable differences in Si, Al, and Fe contents, reflecting contrasting fluid chemistries and geological settings. Trace element analysis revealed depletion in most elements except for enrichments in B, Li, Ga, Be, Sn, and Ta, suggesting advanced melt fractionation and extended melt migration. Rare earth element patterns further distinguished the localities: Okerimi-Oro samples were enriched in light REEs and displayed pronounced Eu anomalies, indicating a lower crustal melt source, while Ijomu-Oro samples showed balanced LREE and HREE enrichments, consistent with mantle-derived melts that experienced crustal contamination. These findings highlight the role of mineralizing fluid composition and host rock interactions in determining tourmaline chemistry and support the use of tourmaline as a petrogenetic indicator in pegmatitic environments.

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1.0. Introduction

Tourmaline is a complex boron cyclo-silicate mineral group famous for its wide compositional diversity and vibrant colour range, making it one of the most valuable and sought-after gemstones worldwide. With the formula $XY_3Z_6(BO_3)_3Si_6O_{18}(O,OH,F)_4$, the tourmaline group is one of the most chemically variable silicates, having many recognized mineral species [1], and an extremely wide range of cation sizes and charges that can occupy the X, Y, and Z sites. Its compositional variability not only influences its colour and gemological properties but also provides important geological insights into its conditions and environments of crystallization. Tourmaline's chemistry reflects the diverse compositions of its host rocks and hydrothermal fluids with the progressive evolution of the hydrothermal system, as well as differences in temperature and pressure of formation [2]. This compositional record provides insight into mineralizing conditions, fluid flow, and possible sources of constituents in hydrothermal systems, especially in magmatic-hydrothermal systems [3], and more importantly, the geological history of the host rock.

Oro, the study area which comprises the localities of Ijomu-Oro, Okerimi-Oro, Afin-Oro, Iddo-Oro, and Agberun is situated within latitudes 8^0 13' 00" to 8^0 19' 00" and longitudes 4^0 52' 00" to 40 57' 00".The area which is underlain by the rocks of the Basement Complex, is prolific in terms of pegmatites occurrences, thereby making it one of the notable localities for gem-quality tourmaline exploitation. Gem-quality tourmaline crystallizes almost exclusively from rare-element LCT-family pegmatites. Studies have revealed the occurrences of several tourmaline species, including schorl, indicolite, and elbaite in these types of pegmatites [4].In Nigeria, particularly in the south western region, gem-quality tourmalines have been actively mined and traded, contributing significantly to the country's mineral economy.Despite the commercial importance of these minerals, comprehensive studies detailing their compositional characteristics and variations remain limited. Understanding the chemical make-up of these gem minerals is essential, not only for proper classification and valuation but also for elucidating the petrogenetic characteristics of their host pegmatites.This study aims to investigate the compositional variations among gem tourmalines sourced from Oro, southwestern Nigeria. Through detailed geochemical analyses, the research seeks to characterize the chemical composition of the tourmalines, identify the factors responsible for their compositional diversity, and infer the geological processes that controlled their formation. The findings will contribute to the broader understanding of tourmaline geochemistry and mineralization in Nigeria and support ongoing efforts in gem exploration and classification within the region.

Geological Setting

Oro study area, lying within the Precambrian Basement Complex terrain of Nigeria, occurs within the Pan African mobile belt. This area lies between the West African craton to its west, the

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Congo craton to its southeast, and the East Saharan block to its northwest[5].The Basement Complex of Nigeria which has a complex geologic history as a result of the different episodes of rock formation spanning from Achaean to Lower Proterozoic, is characterized by a complex assemblage of migmatites, gneisses, schists, and granitic intrusions.The basement is litho-stratigraphically divided into three major groups; the Migmatite-Gneiss-Quartzite Complex comprising gneisses, quartzites, and quartz-schists;the Schist Belts consisting of Para-schists and meta-igneous rocks;and the Older Granite which include granites, pegmatites, and syenites [6].

Lithologically, the study area reflects the typical components of the Nigerian Basement Complex, with the three subdivisions of the complex well represented within the area. The region predominantly features medium- to high-grade metamorphic rocks, including the oldest and most dominant quartz schist, a member of the Migmatite-Gneiss-Quartzite Complex which is associated in a few places by amphibolite, a part of the Schist Belt, while both of them have been intruded in various places by granite and pegmatites, which are members of the Older Granite (Fig. 1).Even though it is rarely exposed due largely to its susceptibility towards weathering, the quartz schist is believed to serve as a host to the other rocks of amphibolite, granite and pegmatites in the area. Where exposed, intense weathering has reduced the quartz schist to low-lying outcrops, with original geological featuressuch as foliation planes largely obliterated and the constituent minerals significantly altered. These weathering effects havehindered accuratemeasurements of geological structures and limited the feasibility of obtaining representative rock samples. At some few locations in the study area, particularly around places where tourmaline mining activities are taking place, the quartz schist is invaded extensively by dark discrete groups of discontinuous amphibolites which have formed into small round, elliptical and isolated bodies of rocks. Towards the northern part of the study area occurs a low-lying, fine to medium grained and highly jointed intrusive body of granite. The granite belongs to the Older Granite suite, a group of intrusive rocks that have intruded into the Migmatite-Gneiss and the Schist Belts, and are believed to have been emplaced during the Pan-African orogeny [7].

Pegmatites, Precambrian in age, belonging to the Older Granite member of the Nigerian Basement Complex have intruded into the older rocks of quartz schist and amphibolite in various parts of Oro, the study area. They occur in various shapes; as small intrusive bodies, as veins and dykes, intruding discordantly into the host older rocks. Two lithologically different types of pegmatites are observed in the study area, exhibiting different mineralogical assemblage, and therefore different chemical compositions. The first and most dominant type of pegmatite occurs as intrusive circular bodies and veins that are observed to intrude into the older quartz schist in various parts of the area. This pegmatite type is seen to contain mainly two mineral types; quartz and feldspars,

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both plagioclase and orthoclase, with muscovite as accessories. The second pegmatite type, which is restricted only to mining excavations, is believed to be hosted within the amphibolite and mainly occur as dykes.This second type is highly enriched in muscovite, apart from quartz and feldspar. They bear the tourmaline minerals which are mined in the area. The tourmaline crystals occur in cavities and along contacts between the pegmatites and host rock. These Nigerian pegmatites were formed during the time span of 562–534 Ma, indicating emplacement related to the end of the Pan-African magmatic activity, and have been sources of metallic and non-metallic minerals [8]. They occur mostly as dyke-like intrusions, which vary from few meters to several kilometres in length and few centimetres to metres in width [9].

2.0. Materials and Methods

Ten tourmaline crystal samples ranging in colour shades from green to blue were obtained, five each from the active mine sites of Ijomu-Oro Dogon-Daji and Okerimi-Oro. Each of the crystals was carefully ground, pulverized and labeled to avoid contaminations and mix-up. The samples were thereafter analyzed for their elemental composition, using the technique of the Inductively Coupled Plasma-Mass Spectroscopy(ICP-MS) at the Activation Laboratories, Canada.The samples' pulverization was to promote rapid and complete dissolution, as the ICP-MS analytical method requires the samples to be introduced as a stable solution to obtain a reliable analysis. An ICP-MS combines a high-temperature Inductively Coupled Plasma (ICP) source with a mass spectrometer. The sample is naturally introduced into the ICP plasma as an aerosol, and the elements in the aerosol are transformed first into gaseous atoms and then ionized towards the end of the plasma. They are then transported into the mass spectrometer through the interface cones. The interface region in the ICP-MS conveys the ions traveling in the argon sample stream at atmospheric pressure into the low-pressure section of the mass spectrometer. When the ions enter the mass spectrometer, they are separated by their mass-to-charge ratio, and then detected by a suitable detector which decodes the number of ions striking the detector into an electrical signal that can be measured and linked to

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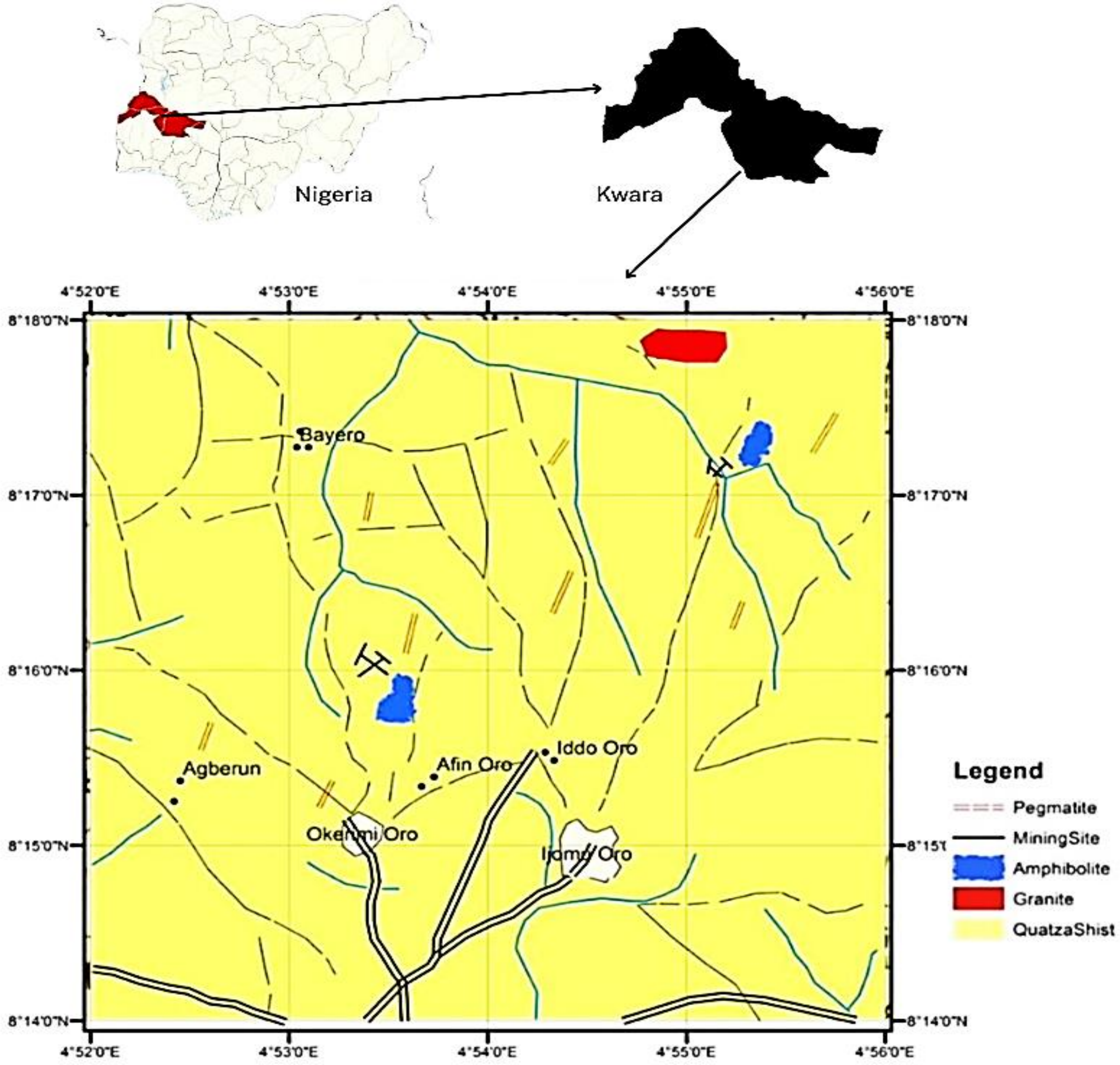

Figure 1: Geological Map of Oro Study Area(This study)

the number of atoms of that element in the sample via the use of calibration standards.

3.0. Results and Discussion

Results of the geochemical analysis revealed similar and moderate enrichments of Si and Al in all the analysed tourmaline (Table 1). While Si ranged from 17.30 wt. % to 19.40 wt. % with a mean, standard deviation(S.D) and median values of 18.40±0.92 wt. % and 18.40 wt. %, respectively, Al ranged from 16.30 wt. % to 22.09 wt. % with its mean± *S.D*and median values of 18.77± 2.40 wt. % and 18.59 wt. % respectively (Table 2). Fe also ranged from 1.83 wt. % to 6.45 wt. %, with mean ±

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S.D values of 4.96± 1.49 wt. % and a median value of 5.47 wt. %. All the remaining major elements showed depletions in all the analyzed tourmaline samples, with some of them measuring below their detection limits. Results also showed some significant compositional variations among the major elements in the analyzed samples, with the greatest variations observed for Al, Fe and Si, with their calculated S.D values of 2.40 wt. %, 1.49 wt. % and 0.92 wt. % respectively. These compositional variations among the samples could have resulted from the changing nature of the mineralizing fluid as it interacts with the host rock compositions, becoming increasingly siliceous, aluminous and Fe-rich in nature [10]. This is practically due to the heterogeneity in the chemistry of their mineralizing fluids, and the geologic settings of the mines in the two localities from where the tourmaline samples were obtained. Previous studies have shown that the composition of tourmaline typically reflects the environments in which it is crystallized [11].On the contrary, samples obtained from same mine presented very narrow compositional variability, particularly for Si and Al, reflecting homogeneity in the chemistry of their mineralizing fluids brought about by the compositional homogeneity of their host rock environments of crystallization. Whereas among the Ijomu-Oro mine samples, Si ranged from 19.00 wt. % to 19.40 wt. % with mean ± S.D values of 19.26 ± 0.17 wt. %, it ranged from 17.30 wt. % to 17.79 wt. % with mean ± S.D values of 17.55 ± 0.18 wt. %amongthe Okerimi-Oro mine samples (Table 3).Also,Al ranged from 16.30 wt. % to 16.80 wt. % with mean ± S.D values of 16.54 ± 0.18 wt. % among the Ijomu-Oro mine samples, while it ranged from 20.37 wt. % to 22.09 wt. % with mean ± S.D values of 20.99 ± 0.76 wt. % among Okerimi-Oro mine samples. The low S.D values obtained among samples from the individual locality implied narrow compositional variation among them, signifying that the samples from the respective mines have crystallized from mineralizing fluids of near similar chemistry, indicatinghomogeneous geological setting for each locality. The major element compositions of tourmaline naturally reflect the environment in which it crystallized [2].The pegmatites which hosted the tourmaline crystalsof the same mine locality are closely related, being hosted by rocks of similar compositions, and point to a common petrogenetic origin being formed through the same geological processes.

Table 1: Compositions of the studied gem tourmaline mineral samples from Oro

Sample locality	**Ijomu-Oro mine site**					**Okerimi-Oro mine site**				
Major Elements (wt. %)	***M01***	***M02***	***M03***	***M04***	***M05***	***R31***	***R32***	***R33***	***R34***	***R35***
	D. Blue	***D. Blue***	***D. Blue***	***D. Blue***	***Blue***	***L. Green***	***Green***	***D. Blue***	***D. Blue***	***Blue***
Si	19.40	19.00	19.40	19.20	19.30	17.52	17.64	17.48	17.30	17.79
Al	16.60	16.50	16.30	16.50	16.80	22.09	21.49	20.37	20.41	20.60
Fe	6.12	5.59	5.60	5.99	4.75	1.83	2.80	5.35	6.45	5.07
Mg	0.34	0.30	0.33	0.33	0.31	0.04	0.01	0.04	0.05	0.02
Ca	0.94	0.93	0.95	0.92	0.94	0.16	0.29	0.08	0.06	0.13

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Na	NA	NA	NA	NA	NA	1.47	1.73	2.11	2.08	2.14
K	0.10	0.20	0.10	0.20	0.10	0.04	0.04	0.04	0.04	0.04
Ti	0.07	0.03	0.04	0.07	0.1	0.02	0.01	0.02	0.02	0.01
Mn	0.74	0.84	0.83	0.76	0.88	0.15	0.73	0.68	0.38	0.53
Cr	0.004	0.004	0.006	0.003	0.004	0.004	0.004	0.006	0.003	0.004
TraceElements (ppm)										
B	>10000	>10000	>10000	>10000	>10000	>10000	>10000	>10000	>10000	>10000
Ba	15	9	12	11	11	23	15	14	17	20
Be	7	14	10	7	10	179	22	16	26	37
Co	10.6	2.8	2.3	9.3	1.6	0.3	0.1	0.8	0.6	0.3
Cs	1.6	1.7	1.7	1.9	1.6	1	1.2	0.2	0.5	0.1
Ga	116	125	101	104	102	130.9	136.6	118.8	58.3	58.7
Hf	5	5	5	5	5	0.2	0.2	0.1	0.1	0.2
Nb	3.1	3.8	3.0	3.0	3.6	19.4	2.6	0.9	0.7	1.6
Rb	5.7	6.0	3.0	3.1	3.8	2.2	3.1	0.6	0.8	0.7
Sn	18.5	24.6	21.7	18.1	25.2	146	29	21	20	20
Sr	33	33	34	35	31	7.4	9.5	10.3	50.3	24.8
Ta	1.1	2.5	1.6	1.5	2.7	96.2	5.8	1.6	2.3	5.8
Th	0.3	0.4	0.3	0.5	0.3	0.3	0.2	0.1	0.1	0.2
U	0.2	0.3	0.5	0.2	0.2	1.2	0.1	0.05	0.05	0.05
V	18	9	12	15	0.3	12	9	10	4	4
W	0.35	0.35	1.5	0.35	0.35	0.25	0.25	0.25	0.25	0.25
Y	0.8	0.4	0.4	0.6	0.5	0.6	0.6	0.3	0.6	0.4
Li	5360	5720	5480	5510	5780	NA	NA	NA	NA	NA
La	0.7	0.7	0.7	0.8	0.7	2.1	1.8	0.9	1.2	1.1
Ce	1.6	1.5	1.9	1.2	1.6	2.5	1.4	1.2	1.5	1.5
Pr	0.1	0.05	0.4	0.2	0.2	0.22	0.15	0.12	0.15	0.16
Nd	0.6	0.8	0.8	0.5	0.7	0.9	0.4	0.3	0.5	0.5
Sm	0.2	0.05	0.2	0.1	0.1	0.17	0.03	0.07	0.03	0.03
Eu	0.05	0.05	0.05	0.05	0.05	0.03	0.01	0.01	0.03	0.03
Gd	0.2	0.2	0.1	0.2	0.05	0.13	0.08	0.03	0.06	0.08
Tb	0.05	0.05	0.05	0.05	0.05	0.03	0.01	0.01	0.01	0.01
Dy	0.15	0.15	0.15	0.15	0.15	0.14	0.06	0.07	0.1	0.09
Ho	0.1	0.1	0.1	0.1	0.1	0.02	0.01	0.01	0.01	0.01
Er	0.05	0.1	0.05	0.2	0.2	0.04	0.02	0.04	0.02	0.04
Tm	0.05	0.05	0.05	0.05	0.05	0.02	0.01	0.01	0.01	0.01
Yb	0.05	0.2	0.2	0.05	0.05	0.03	0.03	0.03	0.03	0.03
Lu	NA	NA	NA	NA	NA	0.01	0.01	0.01	0.01	0.01

Table 2: Summary of major elements compositions of studied tourmaline samples from Oro mine sites (wt. %)

Major Elements	*Range*	*Mean ± S.D*	*Median*
Si	17.30 - 19.40	18.40 ± 0.92	18.40
Al	16.30 - 22.09	18.77 ± 2.40	18.59
Fe	1.83 - 6.45	4.96 ± 1.49	5.47

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Mg	0.01 - 0.34	0.18 ± 0.15	0.18
Ca	.06 - 0.95	0.54 ± 0.42	0.61
Na	1.47 - 2.14	1.91 ± 0.29	2.08
K	0.04 - 0.20	0.09 ± 0.06	0.07
Ti	0.01 - 0.07	0.03 ± 0.02	0.02
Mn	0.15 - 0.88	0.65 ± 0.23	0.74

Table 3: Summary of major elements compositions of studied tourmaline samples from the individual mine in the different localities of Oro (wt. %)

	Ijomu-Oro		**Okerimi-Oro**	
Major Elements	***Range***	***Mean ± S.D***	***Range***	***Mean ± S.D***
Si	19.00 – 19.40	19.26 ± 0.17	17.30 – 17.79	17.55 ± 0.18
Al	16.30 – 16.80	16.54 ± 0.18	20.37 – 22.09	20.99 ± 0.76
Fe	4.75 – 6.12	5.61 ± 0.53	1.83 – 6.45	4.30 ± 1.92
Mg	0.30 - 0.34	0.32 ± 0.02	0.01 - 0.05	0.03 ± 0.02
Ca	0.92 - 0.95	0.94 ± 0.01	0.08 - 0.29	0.14 ± 0.09
Na	BDL	BDL	1.47 – 2.14	1.19 ± 0.30
K	0.10 - 0.20	0.14 ± 0.05	0.04 - 0.04	0.04 ± 0.00
Ti	0.03 - 0.1	0.06 ± 0.03	0.01 - 0.02	0.02 ± 0.01
Mn	0.74 – 0.88	0.81 ± 0.06	0.15 – 0.73	0.50 ± 0.24

BDL = Below Detection Limit

It is remarkable to note that even though variations particularly in Si and Al concentrations do not appear to be apparently responsible for any difference in the physical properties of tourmalines, particularly the colour, but they are observed to adversely influence the distributions of other major and trace elements. The inter elemental associations between the major elements in the study samples, using Pearson correlation reveal some significant levels of positive correlations between some elements while some considerable levels of negative correlations were also observed between some others (Table 4).Al, a very active and prominent element in most geological processes is observed to exhibit very strong negative correlations with all the major elements analyzed. Positive correlations were observed to exist between Si and all the other major elements except Al with which it exhibits strong negative correlation. While a strong negative correlation exists between Al and Si (-.955), positive correlations are observed between Si and all the basic elements analyzed. The negative correlation existing between Si and Al suggests possible substitutions among them. A positive correlation was observed for Si and Mg (.977) on one hand and Si and Ca (.985) on the other hand, showing that both Mg and Ca have affinities for Si. While significant positive correlations are observed for the pairs Si-Ti (0.631) and Si-Mn (0.729), the pairs Al-Ti (-0.639) and Al-Mn (-0.762) are negatively correlated

Table 4: Statistical correlation coefficients for major elements compositions of tourmaline samples from Oro

Si	***Al***	***Fe***	***Mg***	***Ca***	***Na***	***K***	***Ti***	***Mn***

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Si	1								
Al	-.955**	1							
Fe	0.416	-.632*	1						
Mg	.977**	-.976**	0.495	1					
Ca	.985**	-.946**	0.365	.976**	1				
Na	-0.02	-.984**	.934*	0.121	-0.595	1			
K	.748*	-.808**	0.421	.802**	.804**	.c	1		
Ti	0.631	-.639*	0.488	.689*	0.612	-0.09	0.615	1	
Mn	.729*	-.762*	0.446	.676*	.740*	0.485	0.574	0.277	1

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).
c Cannot be computed because at least one of the variables is constant.

Since aluminum and silicon are major components which are usually immobile during most geological processes such as metamorphic and hydrothermal processes, variation diagrams of the various elements plotted against them may assist in defining the behaviour of these elements in the tourmaline minerals. Binary plots of Si against Al (Fig. 2a) and Mg versus Al (Fig. 2b) all yielded well-defined negative trends, indicating significant negative correlations among the two pairs of elements. All the basic major elemental contents of the analysed Oro tourmaline samples were positively correlated among themselves and they also showed positive correlations with the alkaline elements, indicating their levels of affinities for one another. The binary plots of Ca versus Mg (Fig. 3a) and K against Mg (Fig. 3b) all displayed discernible positive trends, portraying strong positive correlations among each of the pairs. The heterogeneity in the geological settings of the two mines was also exhibited in all the binary plots by the diversity displayed between the two groups of tourmaline samples obtained from the mines, whereas the clustering of the samples obtained from each of the mines revealednear homogenous compositions, reflecting the homogeneity in the geological settings of their environments of crystallisation.

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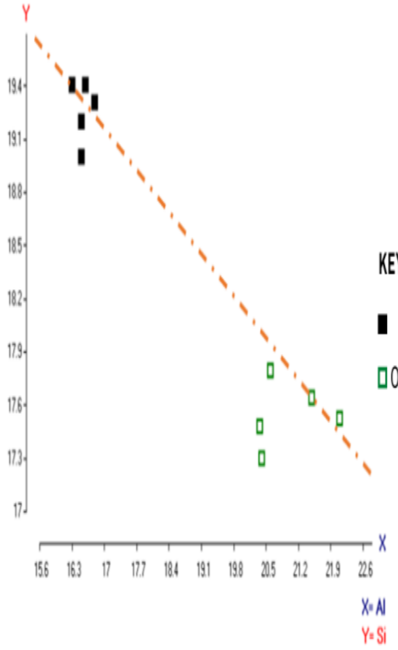
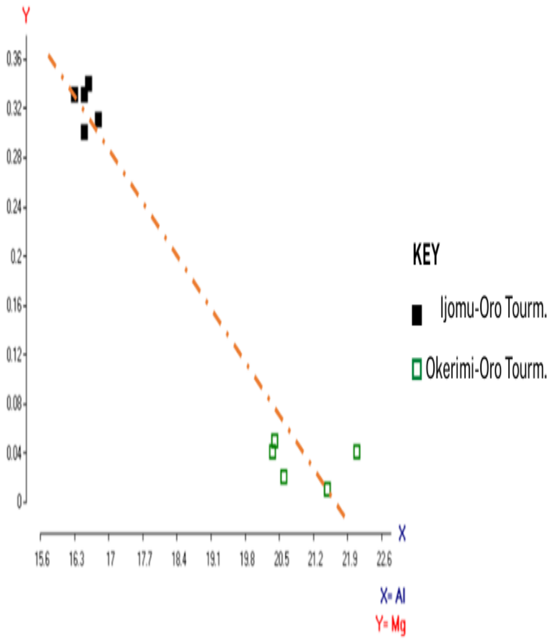


Figure 2a: The binary plot of Al against Si for the tourmaline samples from Oro



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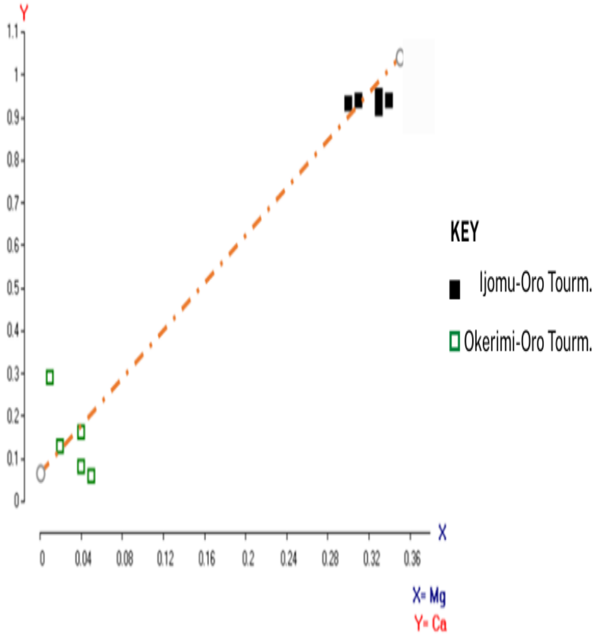

Figure 3a: The binary plot of Mg against Ca for the

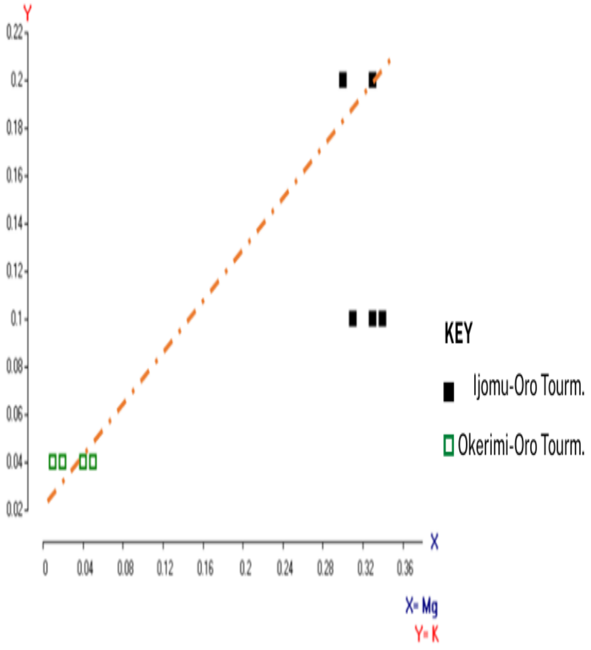

Figure 3b: The binary plot of Mg against Ca for

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tourmaline samples from Oro

There is some correspondence between the chemical composition of tourmaline and its colour, although this is not always the case [12]. Compositional variations in Si and Al among the analyzed tourmaline samples from Oro are not observed to have any adverse effect on their colours. This is because some samples which are seen to possess same colour are seen to bear varied amounts of these elements, whereas samples of different colours are observed to measure nearly the same values of these elements. Most elements found in tourmaline minerals do not produce colour because their electronic configurations remain stable. Silicon, aluminum, calcium, lithium, beryllium, boron, carbon, nitrogen, etc. remain white and colourless. Tourmaline colour is directly linked to its transition elements contents, especially Mn^{2+}, Mn^{3+}, Fe^{2+}, Fe^{3+} and Ti^{4+}[13]. These are elements known for forming stable ions with partially filled d-orbitals. [14] reported Fe, Mg, Mn and Cu as the chromophores in tourmalines. Out of these chromophores mentioned as responsible for colours in tourmalines, only Fe appeared to show some significant presence in the analysed Oro tourmaline minerals. All the others were depleted, with some of them measuring below detection limit (Na). This therefore implied that Fe seemed to be the only chromophore responsible for colouration in the Oro tourmaline minerals.[10] actually showed that Fe is chiefly responsible for tourmaline’s colour variation among the studied tourmaline samples from southwestern Nigeria. It can be observed that the green coloured tourmaline samples, R31 and R32 have the lowest Fe values of 1.83 wt. %, 2.80 wt. % respectively, while the blue coloured ones have much higher Fe values ranging from 4.75 wt. % to 6.45 wt. % (Table1). It is therefore observed that the higher the Fe concentrations, the deeper the greens and the blues. The values of Fe in the analysed samples were directly proportional to the intensity of the greens and the blues. It is a widely recognized theory that the main controlling factor for colour in tourmaline is the presence or absence of iron (Fe)[15].

the tourmaline samples from Oro

The analysed tourmaline samples are generally depleted in trace elements except for a few incompatible elements, especially the large ion lithophile elements (LILE) such as boron, a major phase in tourmaline minerals which measures above 10,000ppm, thus existing as a major element in all the samples analysed. Li, another major phase in tourmaline, especially the light coloured ones, is also enriched in the samples where it is analyzed. Li ranged in concentration from 5360 to 5780 ppm with an average value of 5570 ppm. Ga, another incompatible element is slightly enriched in most of the samples analyzed, ranging from 58.30 to 136.60ppm. A tourmaline sample, R31 obtained from Okerimi-Oro mine was observed to be exceptionally enriched in most of the incompatible elements, including Be (179ppm), Ga (130.90), Sn (146ppm) and Ta (96.20ppm). The pegmatite-forming melt from which this sample has crystallized must have traveled a very long distance from its parental source,since[16] has shown that the farther a melt travels, the more fractionated and enriched in incompatible elements the resulting pegmatite will be.

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The compositional variability observed between the two groups of tourmaline samples obtained from the different mines still persists in their rare earth elements (REE) concentrations. The REEswere more enriched, but less widely varied in Ijomu-Oro samples than in Okerimi-Oro samples as displayed in the REE pattern (Fig. 4).This implied that the REE content showed no obvious dependence on either the major or trace element compositions, suggesting that paragenetic conditions are the predominant controls on REE distributions in the tourmaline samples. The Okerimi-Oro tourmaline samples were more enriched in the light rare earth elements (LREE) than the heavy rare earth elements (HREE), indicating a lower crust source for the residual melts from which the minerals have crystallized. All the samples exhibited similar chondrites-normalized REE patterns (Fig. 4), virtually displaying slight LREE-enriched and HREE-depleted patterns and generally exhibiting fractionated asymmetric concave-upward shapes, with varied Eu anomalies, an indication for granite-related pegmatitic tourmalines (Fig. 4). While one sample was seen to display no Eu anomaly, the others exhibited well-pronounced anomalies, two positive and two negative Eu anomalies.The REE patterns of the Ijomu-Oro samples exhibited different characters, generally displaying uniform LREE and HREE enrichment patterns and also exhibiting fractionated asymmetric concave-upward shapes, with varied degree of positive Eu anomalies. The uniform enrichment in both LREE and HREE suggests that the melt from which the tourmaline minerals were crystallized have originated from materials of the mantle with contamination from the lower crust.

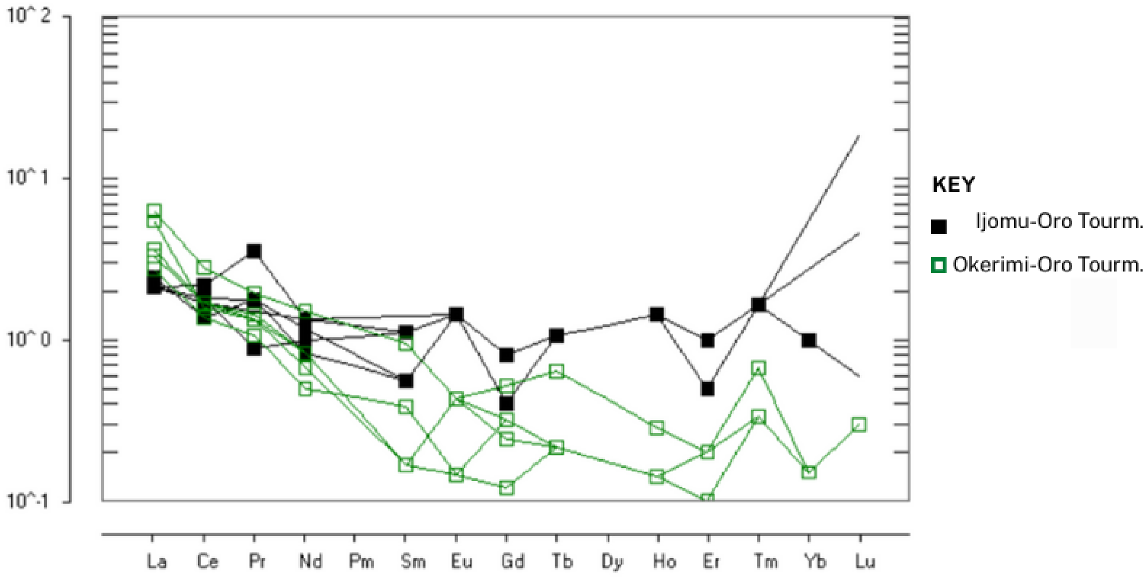

Figure 4: Chondrites-normalized REE patterns of the analyzed pegmatitic tourmaline samples from Oro study area.

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Conclusion

The moderate and consistent enrichments of silicon (Si) and aluminum (Al) in the tourmaline samples from Ijomu-Oro and Okerimi-Oro confirmed the aluminosilicate nature of the minerals. Despite similarities in overall composition, notable variations existed between samples from the two mines, primarily in Al, Fe, and Si contents. The observed slight geochemical differences between the pegmatitic tourmalines from the different localities in Oro have resulted from the compositional differences in their respective residual pegmatitic melt and the host rock influence. In contrast, tourmaline samples from the same mine exhibited narrow compositional variability indicating homogeneous fluid chemistry and petrogenetic conditions. The study established that the composition and therefore mineralogy of tourmalines are virtually dictated by the mineralizing fluid and the environments of crystallisation, particularly the host rocks' chemistry.Iron (Fe) is identified as the primary chromophore influencing the colour of the tourmaline, with higher Fe concentrations corresponding to deeper blue and green hues. Other potential chromophoric elements were either depleted or below detection levels. The trace element profile showed general depletion except for enriched incompatible elements such as B, Li, and Ga, with exceptional enrichment in a few samples, particularly from Okerimi-Oro, suggesting long melt migration and high degrees of magmatic differentiation. Rare earth element (REE) patterns further highlighted the geochemical divergence between the samples from the two localities. Okerimi-Oro samples were more enriched in light REEs, indicating a lower crustal melt source, while Ijomu-Oro samples showed uniform LREE and HREE enrichments, implying a mantle-derived melt with lower crustal contamination. The chondrite-normalised REE patterns and Eu anomalies across samples supported their crystallisation from granite-related pegmatitic melts. Overall, the chemical signatures of the tourmaline samples reflected both the petrogenetic history of their host pegmatites and the compositional diversity of the mineralizing environments.

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Authors Contribution

Jimoh, Razak O.: Conceptualization, Investigation, Validation, Methodology, Tourmaline geochemistry, Interpretation, Writing original draft, Supervision.

Abdulkadir Sagir: Sample preparations and analysis, Geological mapping and local geology, Resources.

Onoduku, Usman S.: Geological setting, Geological mapping, investigation and validation.

Afolabi, Adegoke. O.: Geological mapping and local geology, Software plots and interpretation.

Ayuba, Rufai: Geological mapping and local geology, Sample preparation and analysis.

Ogunjimi, Rebecca O: Geological mapping and local geology, Writing original draft

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