

Aquamarine Gemstone

Nazia Sultana* and Sankara Pitchaiah Podila

Department of Geology, Acharya Nagarjuna University, Nagarjuna Nagar, Guntur-522510, Andhra Pradesh, India

ABSTRACT

Aquamarine gemstone is one of the Beryl mineral varieties with Beryllium aluminium silicate composition. Its bluish green color caused from Fe^{2+} ions puts it as a special variety. It is used in jewellery and has some industrial applications. This beautiful gemstone is reported from few countries only, namely India, Brazil, Canada, China, Italy, Pakistan, Russia, Ethiopia, Madagascar, Mozambique, Namibia, Nigeria, United Kingdom, United States, Mexico and Vietnam. The present study collected its occurrences from various parts of the world and studied the variation of oxides analyzed from Aquamarine. It is observed that SiO_2 ranges from 64.99% to 72.48%, Al_2O_3 : 11.63% to 19.91%; BeO : 12.9% to 13.79%; FeO : 0.11% to 5.03%; CaO : 0.01 % to 0.83%; MgO : 0.00% to 1.93%; Na_2O : 0.10% to 3.53%; K_2O : nearly zero to 3.31% and MnO : 0.00% to 0.06%.

Keywords: Aquamarine Gemstone, Chemical Analysis, Jewellery, Variation of Oxides

I. INTRODUCTION

The name "beryl" is derived from Greek beryllon which referred to a "precious blue-green color-of-sea-water stone" (Figure 1).



Fig.1 Aquamarine Crystal

(Source: <https://commons.wikimedia.org>)

It is a mineral composed of beryllium aluminium cyclosilicate with the chemical formula $\text{Be}_3\text{Al}_2(\text{SiO}_3)_6$. Beryl is a single mineral with many types. There are six well known types of beryl. Each type is known because of its distinctive color (Table 1).

Of all of the varieties, Emerald and Aquamarine are the most popular varieties, because of their beauty. Aquamarine is a light bluish green form of beryl. Its

Table 1. Beryl Varieties

Variety	Color
Emerald	Green
Aquamarine	Bluish green
Heliodor	Yellow
Bixbite	Red
Morganite	Pink
Goshenite	Colorless

specific color comes from impurities of iron that lie within the beryl. The exact color of the Aquamarine itself is dependent on where the impurities are located in the beryl. The most sought after color is pure blue. The pale blue color of Aquamarine is attributed to Fe^{2+} . Fe^{3+} ions produce a golden-yellow color, and when both Fe^{3+} and Fe^{2+} are present, the color is a darker blue as in maxixe. Decoloration of

maxixe by light or heat, thus may be due to the charge transfer between Fe^{3+} and Fe^{2+} .

Aquamarine is found commonly in granitic pegmatites, mica schists and limestones. It is found in secondary deposits, although much of the darkest material has come from the primary pegmatites. Aquamarine has usually heat treated to obtain its optimum blue, heliodor may be heat treated to turn from yellow to Aquamarine blue. (<http://www.geologyin.com>).

Uses

- Beryl contains a very rare element called beryllium, which is only found in about 100 minerals.
- It is extensively used in jewelry.
- Rings, earrings, and bracelets are made from Aquamarine.
- Used in the production of wire.
- It is also being used on space shuttles.

II. WORLD DISTRIBUTION

The world distribution of Aquamarine is presented here.

India

In India Aquamarine is reported in pegmatites of Karur - Kangayam region of Tiruchurapalli district, Tamil Nadu. Salem district is also said to be an important place for Aquamarine. According to Iyer (1961), Aquamarine is recovered from Melukote in Hassan district of Karnataka and Goshenite and Aquamarine in Aravalli region. Further, he had reported occurrence of several fine crystals of Aquamarine from Sunjam sapphire mines in Kashmir. Greenish blue Aquamarine has been reported from Ooruttamalam and Uzhamalakkal (UNDP report, 1983). (Mishra and Mohanty, 1995) reported Aquamarine from Orissa. Mathew, 1998 also carried out studies on Colorless, blue, blue green, green and

yellow beryls from Sambalpur, Sabarnapur and Bolangir district in Orissa. Badmal in Sabarnapur district happens to be the central place for the occurrence of beryl bearing pegmatites.

Nazia Sultana and Sankara Pitchaiah have reported Aquamarine from Putrela, Krishna District, Andhra Pradesh (Unpublished) (Figure 2).

Koivula and Kammerling (1989) have reported Aquamarine from Kangyam. They studied the gemological properties of the sample and the results are the most notable feature of this stone other than its exceptional color was the presence of strain with a "laminated" appearance that was quite evident in polarized light. The strain also manifested itself in the form of a biaxial interference figure that was seen in only some areas of the stone.



Fig. 2 Aquamarine from Putrela, India

Panjikar and Panjikar (2014) found in Pallapatti village, Karur district of Tamil Nadu. The characteristic microscopic inclusions were a variety of fluid inclusions, two phase, three phase, liquid films, liquid filled capillaries, feathers, healed feathers, large cavities filled with original magmatic fluids. These fluid inclusions were observed to be of different generations with specific orientation with respect to the c-axis.

Choudary (2014) reported a transparent grayish blue oval mixed cut was submitted for identification at the Gem Testing Laboratory in Jaipur. They carried out the standard gemological properties along with absorption spectra and the pleochroic color directions were sufficient to identify this stone as Aquamarine. The study concluded that most intense dichroism are seen in Aquamarine.

Brazil

Filho et al., (1973) carried out chemical analyses and crystallographic and some optical data have been obtained for the 28 samples of beryl from Bahia State, Brazil. From statistical analysis increase of Fe and (Fe+Mn+Mg) percentage has a positive correlation with α but no influence on c, which in turn has a close positive correlation with Li and is negatively correlated with Be are observed. A positive correlation also exists between sodium and the parameter α .

Blak et al., (1982) made an attempt to compare blue and green beryl crystals from the region of Governador Valadares, Minas Gerais, Brazil. The infrared spectra show that the alkali content in the blue beryl is mostly at substitutional and /or interstitial sites and in green beryl is mostly in the structural channels. The Optical Absorption spectra show two types of Fe^{2+} . Thermal treatments above 200°C in green beryl cause the reduction of Fe^{3+} into Fe^{2+} accompanied by a change of color to blue. The blue beryl color does not change on heating.

Proctor (1984) found Aquamarine in the northeastern part of Minas Gerais; millions of carats have been mined since the discovery of the Papamel crystal in 1910.

Bank et al., (2001) reported Aquamarine from Santa Maria in Minas Gerais, Brazil. They have studied the optical properties and the results are as follows; RI n_e

1.578-1.581, n_o 1.585-1.588, birefringence 0.007-8; SG 2.68-2.70.

Viana et al., (2002) selected samples from four pegmatites in the northeastern Minas Gerais State, Brazil. The crystals were taken from the wall and intermediate zones and from pockets. The color of beryl seems to be dictated by the relative proportions of Fe^{3+} in the octahedral sites and of Fe^{2+} in the channels. Thus, deep-blue samples have little Fe^{3+} , whereas greener samples have more Fe^{3+} or less channel Fe^{2+} .

Nassau (1996) examined 43 high quality faceted beryl of recent Brazilian origin were examined. The study carried out the identification and fade testing of maxixe beryl, golden beryl and green Aquamarine. They concluded the five yellow and nine greenish large, high quality aG and PH beryls of recent Brazilian origin are non-fading golden beryls and non-fading greenish Aquamarines, respectively.

Canada

Various workers have studied True blue Aquamarine from Canada.

Groat et al., (2005) have reported Emerald and Aquamarine from Yukon Territory, Canada. The study reviews the geology, mineralogy, and origin of the gem varieties of beryl, including emerald (green) and Aquamarine (blue). The geological conditions needed to bring Be in contact with Cr and/or V are briefly discussed, as are the factors to consider and techniques to use in exploring for gem-quality beryl.

Linnen et al., (2006) have reported "True Blue" Aquamarine from Pelly Mountains in south-central Yukon Territory. The Aquamarine most likely originated through the remobilization of Be and Fe from the syenite by metamorphic fluids. This is quite unlike the origin of typical gem-quality Aquamarine, which forms in granitic pegmatites.

Turner et al., (2007) discovered Aquamarine in the Pelly Mountains, southern Yukon Territory, Canada.

To explain the formation of gem beryl, and consequently exploration parameters, applied in Yukon involve late-stage magmatic fluids. Evidence gathered in this study point to a metamorphic origin for the mineralizing fluid and a local derivation of vein constituents, which distinguished the fluids at True Blue from other intrusion-related beryl-forming fluids in the northern Cordillera.

Groat et al., (2010) discovered dark blue Aquamarine and beryl in the Yukon Territory. Unfortunately, the amount of electron and nuclear density is probably too small to be seen on the difference-Fourier maps, and consequently we are unable to confirm that IVCT involving Fe at the 6g position is responsible for the blue color of our samples. Thus the definitive explanation of the blue color of beryl is still lacking.

Lee and David, (2010) studied the rare zoning from dark blue to light blue Aquamarine-bearing section of the dyke in Zealand station, Canada. The deposit contains locally abundant beryl mineralization; there are also variable amounts of molybdenite, wolframite, and scheelite. The beryl samples collected all have micro fractures, although the presence of gem-quality beryl samples is possible beneath the zone of deep weathering.

Beal et al., (2010) reported Aquamarine and molybdenite deposit in Zealand Station, New Brunswick. They have concluded that Aquamarine and molybdenite occur in quartz veins and greisens pockets associated with late-stage northwest-trending pegmatite-aplite dykes with a beryl-rich section and related pegmatite dykes.

Cerny and Hawthorne (1976) concluded that probable error should be between ± 0.5 and ± 1.0 wt%. Beryl with $n_w < 1.580$ contain subordinate amounts of Cs and $n_w > 1.590$ is characteristic of Cs-rich varieties from inner zones of pegmatites that contain not only abundant lithium, but also tend to contain pollucite.

China

Zhaolin et al., (1994) identified the Physicochemical conditions of the formation of Aquamarine in Mufushan Grano pegmatite deposit, Hunan Province, China. The study concluded that Beryllium in the pegmatite was transported mainly in the form of $\text{Na}_2[\text{Be}(\text{CO}_3)_2]$, with part of it is being complexed with Cl^- and SO_4^{2-} . During the generation and evolution of the pegmatite, equilibrium might have been reached in the solid-melt-fluid or solid-fluid system. The intergranular solutions may have reacted with the early crystallized minerals, resulting in potash-feldsparization, albitization and muscovitization during which the ore-forming elements were mobilized and transported in favour of ore deposition.

Ruzeng et al., (2007) have studied Aquamarine from Altai, Siukiang, China and they carried out their study effect of heat treatment on colour, quality and inclusions. They concluded that treatment is done at 480-500°C and results in both colour change and changes to the inclusions. The nature of these changes is illustrated and the appearance of tiny black inclusions is attributed to carbon, which resulted from reduction of original fluids in the inclusions.

Italy

Bocchio et al., (2009) investigated Aquamarine samples from Central Alps, Italy. The study concluded that typical gemological properties for Aquamarine, including Iron absorption features and is characterized by low alkali content.

Spinolo et al., (2007) observed a variety of beryl inclusive of Aquamarine, heliodor and goshenite. They considered the colour centers absorption, their thermal instability and contribution to the color of the crystal and they observed first time spin-forbidden transitions of Fe^{2+} in beryl; the attribution

has been reached by comparison with aqueous solutions containing the Fe^{2+} ion.

Pakistan

Agheem et al., (2014) studied a variety of gemstones like beryl (Aquamarine and goshenite), along with other gemstones being mined in the Shigar valley, Skardu, Pakistan. The study carried out the chemical composition and origin, which suggest that the Beryl, Tourmaline, Garnet, Apatite, Topaz and fluorite are occurring in zoned pegmatites. The only difference in the chemical composition of both the varieties is the difference in FeO contents. The Aquamarine has higher amount of FeO as compared to goshenite.

Yang Hu and Ren Lu (2018) examined the Aquamarine samples from the Shigar Valley in Pakistani, to explore the gemological and other properties. The study concluded that the Pakistani samples were low-alkali Aquamarine colored by Fe ions rather than irradiation (i.e., Maxixe beryl).

Kim and Shin (2014) investigated gemological characteristics of Aquamarine from Gilgit-Baltistan. It occurs in association with big veins of Be-rich coarse pegmatite. The results of chemical analyses and infrared absorption spectra indicate that the Aquamarine is low alkali-bearing beryl with considerable CO_2 .

Badar et al., (2017) collected Aquamarine from pegmatite rocks in Shigar mines, Skardu valley. They concluded that the impurity elements Fe, Ca and K detected in the Shigar sample by XRF elemental analysis indicate the structural substitution that possibly changed the lattice parameters of the sample. The analysis of X-ray diffraction patterns showed the presence of quartz as minor traces with a major phase of Aquamarine in beryl variety.

Russia

Gerasimova et al., (2014) studied inclusions in Aquamarine from Suprunovskoye pegmatite deposit in Russia. Using Raman Spectroscopy they observed

the fluid inclusions, liquid and solid inclusions in Aquamarine.

South Africa

Ethiopia

Laurs et al., (2012) discovered Aquamarine in Southern Ethiopia, which is blue –green in color. Multiple mining areas are active; in the area and the gemstone is collected from an eroded mountain side with a large exposed pegmatite.

Madagascar

Danet et al., (2012) described the interesting inclusions in Aquamarine from Ambatofotsikely area, Madagascar. They carried out the Raman analysis clearly identified the various inclusions i.e., reddish brown platelets were hematite, whereas ilmenite was present as black platelets, black needles, and distinctive dark gray dendritic inclusions. This marks the first time documentation of ilmenite dendrites in Aquamarine.

Chankhantha and Thanasuthipitak (no year) made a study on heat treatment of Aquamarine and Morganite from Madagascar and the result of Aquamarine is alkali-poor beryl. They confirmed that the broad band of Fe^{2+} at 820 nm are attributed to ferrous ion being on the octahedral site since after heat treatment, this peak is slightly increase in intensity due to the converting of ferric ions (Fe^{3+}) at the octahedral site to ferrous ions (Fe^{2+}). The ferrous iron in channel site, however, was not affected by heating even though it plays an important role on blue coloration in Aquamarine.

Bunnaq and Wanthanachaisaeng (2014) a total of 80 rough samples, unconfident source which the merchant selling as Madagascar stone. The study concluded that both atmospheric and reducing conditions can increase blue in Aquamarine because both conditions can cause Fe^{2+} - Fe^{3+} charge process. However, the reducing condition seems to give a

better blue because this condition can also increase Fe^{2+} in channel site.

Danner (1989) examined Medium-dark blue Aquamarines from Tongafeno, Madagascar. His study concentrated to analyse the gemological properties and to compare them with those with similar properties recorded from other localities. Their characteristic dichroism, inclusions, absorption spectrum, and high physical properties are remarkable and can readily differentiate from those from other localities.

Mozambique

Figueiredo et al., (2008) observed the special effects on Fe, K-edge of analyzed blue beryl crystals in Licungo pegmatite (Mozambique). Since a tetrahedral coordination was expected to produce a distinct combination of pre-edge peak intensities, the actual pattern suggests that Fe is mainly in octahedral sites within the beryl crystal, preferably replacing Al rather than Be in the tetrahedral sites. This substitution is possibly responsible for the blue colour.

Namibia

Cairncross et al., (1998) revealed for the first time, both gemological and geological information on topaz, Aquamarine and other beryls from miarolitic pegmatites in Namibia. The study concluded that the gemological properties of the Aquamarine are consistent with known parameters.

Lum et al., (2016) have reported Aquamarine from Erongo, Namibia and compared these with other localities worldwide. The study concluded that Aquamarine range from Pale blue to deep blue with marked color zoning. Numerous cracks are present in the samples examined, and these are usually filled with iron oxides. Inclusions species encountered in the beryl samples are schorl, quartz, muscovite, feldspar, iron oxides and cassiterite, clearly reflective of the host pegmatite mineralogy. Aquamarine and

green beryl contains iron as the main chromophore while goshenite is devoid of chromophores.

Nigeria

Lind et al., (1986) have reported Aquamarine and emeralds of gem quality from Jos in Nigeria. The authors observed several characteristics like crystals with colour zoning. Colour intensities are caused by strongly varying concentrations of V, Cr and Fe and By microscopic investigations, a distinct growth zoning parallel to the basal pinacoid, the hexagonal dipyrmaid and parallel to the first-order prism was observed in Aquamarines and emeralds, as well as two different types of two-phase inclusions.

Schwarz et al., (1996) identified the emeralds and green beryls from Nigerian and to distinguish between Nigerian emeralds and those from other localities. They concluded that the growth structures and fluid inclusions are extremely common and the later ones show a large range of features including Colombian-type three-phase inclusions. For Nigerian emeralds that show an inclusion pattern similar to that of Colombian emeralds, the easiest distinction is by absorption spectroscopy. The Nigerian emeralds show 'mixed spectra' with peaks attributable to Cr^{3+} , Fe^{2+} , Fe^{3+} and $\text{Fe}^{2+}/\text{Fe}^{3+}$, whereas the spectra of Colombian emeralds, as a rule, are largely free of Fe-components.

United Kingdom

England

Watters (1963) discovered light blue beryl in the Canaan. Although the analytical data are inadequate for a complete discussion, it is suggested that those parts of the crystal with higher refractive indices contain correspondingly higher amounts of total alkalis (mainly Na₂O) and more iron than the parts with lower indices. In the apparently isolated occurrence of this beryl, such chemical variation may be a result of slow crystallization, with considerable

variation in the composition of the fluids furnishing ions for the growth of the crystal.

United States

Jacobson (1993) discovered the deposits of Aquamarine in the United States as major and minor deposits. The majority are Colorado, Idaho, Western Maine, Western new Hampshire. The minor occurrences are from Alabama, California, Colorado, Connecticut, Georgia, Massachusetts, New Mexico, North Carolina and South Dakota. The undeveloped areas are Arizona, Maine, and Utah.

Francis et al., (2016) examine the mineralogy of Aquamarine in Stoneham area pegmatites located in Maine. North America's two largest faceted Aquamarines (137.2 and 124.9 carats) are from moderately evolved, beryl-type pegmatites in Stoneham. There is significant potential for future Aquamarine production from the Stoneham area, both from established locations such as the Aldrich quarry and from deposits yet to be discovered.

Mitchell et al., (2003) reported chemical composition of blue beryl in Logtong, northwestern BC. They compared its chemical affinity with known gem occurrences from around the globe. On the basis of Fe content, the Logtong beryl can be classified as Aquamarine, although the presence of gem-quality Aquamarine at this locality has yet to be established. Muntyan (2013) rediscovered of long lost Aquamarine from Sierrita mountains, Arizona. There are several localities reported Aquamarine in Santa Teresa Mountains of Graham County to contain at least grains of beryl, most notably from Cochise County in the Swisshelm and Dos Cabezas mountains; in Mohave County in the Aquarius Mountains; in Maricopa County in the White Pichaco Mountains; and in Pima County in the Sierrita Mountains. Aquamarine is found as slender, simple hexagonal crystal "pencils," to 9 inches in length, but commonly 1.5 inches or less, of cloudy, sky-blue color either

embedded in white quartz, enclosed by feldspar, or in contact with biotite. Rarely are the Aquamarine crystals found in radiating sprays. Also, sky-blue Beryl, variety Aquamarine, is found as slender, simple hexagonal crystal "pencils," to 9 inches in length, but commonly 1.5 inches or less, of cloudy, sky-blue color either embedded in white quartz, enclosed by feldspar, or in contact with biotite. Rarely are the Aquamarine crystals found in radiating sprays.

Parkin et al., (1977) have studied on Mossbauer spectra of natural blue kyanites and beryls from Colorado is proof of the existence of significant proportions of Fe^{2+} ions replacing Al^{3+} ions in octahedral sites in each mineral. Not only do such observations establish the presence of the $\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$ or $\text{Fe}^{2+} \rightarrow \text{Ti}^{4+}$ CT transitions, but they necessitate assignments being made of spectral bands in the absorption spectra for Fe^{2+} spin-allowed CF transitions. The energies of these CF bands must be higher than those encountered in the spectra of most ferromagnesian silicate because Fe^{2+} ions occupy smaller Al^{3+} sites in the kyanite and beryl structures.

Ahline and Salimi (2017) described that mysterious iridescence in Aquamarine crystal on calcite matrix owned by Lucas Fassari (Costa Mesa, California). The study concluded different Refractive index than the host material, producing a rainbow effect and they hypothesize that the cloud-like stringers could be creating dislocations, producing a structure capable of generating interference colors in the localized region just above the stringers.

Kane (1985) identified interesting 9.66ct bicolored modified Emerald cut stones was sent to Los Angeles Laboratory for identification. The study concluded that subsequent testing revealed that this stone was beryl and this is the first time that we have seen a bicolored beryl consisting of Aquamarine and Goshenite.

Mexico

Ostrooumov (2016) discovered transparent blue crystals with hexagonal-prismatic habit in a granitic pluton in the hills of Guadalcázar municipality, San Luis Potosí State, in north-central Mexico. They carried out the UV-Vis- NIR, infrared reflection, and Raman microprobe techniques, as well as standard gemological testing and confirmed the crystal as Aquamarine.

New Jersey

Nassau et al., (1976) observed the formation of a deep blue color center in beryl by a variety of penetrating radiations. If the original beryl is yellow or green, the resulting color can be a green or blue-green. This color center cannot be induced in just any beryl, and the nature of the required precursor is presently unknown. It does not appear to involve transition metals, alkalis, or water. The color center is best characterized by the narrow absorption bands in the ordinary ray only, giving a quick test by examination in polarized light. Two variants exist. The second, termed maxixe-type, can be produced in a significant fraction of irradiated beryls of random origin, and there is here no clear evidence for a natural occurrence.

Nassau and Wood (1973) observed an anomalous dichroism in samples and an unusual narrow band spectrum in the red and yellow regions. In all the cases the color is bleached by exposure to daylight or on heating and can be recovered by neutron or gamma-ray irradiation. A color center not involving a transition metal such as Fe, Co, Cu, etc., is indicated. Examination of 23 faceted "Sapphire" blue beryl gemstones by gamma-ray spectroscopy indicated samples had definitely been colored by neutron irradiation; the others may or may not have been treated by irradiation.

Vietnam

Six Aquamarine crystals are collected and subjected to the analysis (Huong et al., 2011) from eluvial deposits using standard gemological techniques. The authors concluded that Aquamarine contains low concentrations of alkali ions, and relatively high amounts of iron and cesium.

According to Huong et al., (2012) Aquamarine is a known mineral from northern Vietnam at Thuong Xuan. As per Vietnamese dealers, a large volume of pale Aquamarine from Vietnam has been irradiated in Laos and then sold back on the domestic market as natural heliodor.

Fridrichova et al., (2015) Collected samples of Aquamarine and Heliodor from Vietnam and treated by heat. The samples were exhibited cracks and fissures, reduced Fe, changes in colour and clarity in different heated degrees.

Other studies

Nikbakht et al., (2016) Geological Survey of Iran were provided the gemstone samples, i.e., topaz from Pakistan, opal from Australia, and a pale blue-green color Aquamarine with an unknown origin. The results confirm the ability of (Ion beam induced luminescence) IBIL for analyzing weakly luminescent gemstones, such as Aquamarine. Moreover, the presentation of new luminescence bands, like the intense bands of 4.36 eV and 3.57 eV for topaz and opal respectively, reveals the existence of some unknown luminescence activators in the samples.

Adamo et al., (2008) examined a total of 25 natural, treated and synthetic blue beryl specimens from different origins in Brazil, Nigeria, Canada. They concluded that careful observation of pleochroism, fluorescence, and internal features (with magnification) can provide useful indicators for gemologists with basic equipment. More-sophisticated techniques such as UV-Vis-NIR and

mid-infrared spectroscopy, as well as chemical analysis, can provide clear proof of the identification.

Physical and Optical Properties

Physical and optical properties of Aquamarine are shown in Table 2.

From the literature chemical analysis of 14 Aquamarine samples have taken from 8 countries Brazil, Canada, China, Europe, Nigeria, Pakistan, United States and Vietnam (Tables 3a and 3b). Variation of oxides in weight percentage is shown in figures 3a to 3i.

Chemical Composition

Table 2. Physical and optical properties of Aquamarine

Physical properties	Aquamarine	Optical Properties	Aquamarine
Color	Bluish green	Refractive Index	1.577-1.583
Crystal System	Hexagonal	Pleochroism	Dichroism
Crystal Habit	Prismatic	Ultraviolet Fluorescence	Inert
Fracture	Conchoidal	Transparency	Transparent -Translucent
Cleavage	Imperfect	Birefringence	0.005-0.009
Hardness	7.5 to 8	Dispersion	0.014
Specific Gravity	2.66 to 2.80	SR/DR/AGG	Double refractive (DR)
Streak	Colorless	Phenomena	None
Luster	Vitreous	Inclusions	Rain and needle like inclusion, Mica flakes

Table 3a. Chemical analysis of Aquamarine

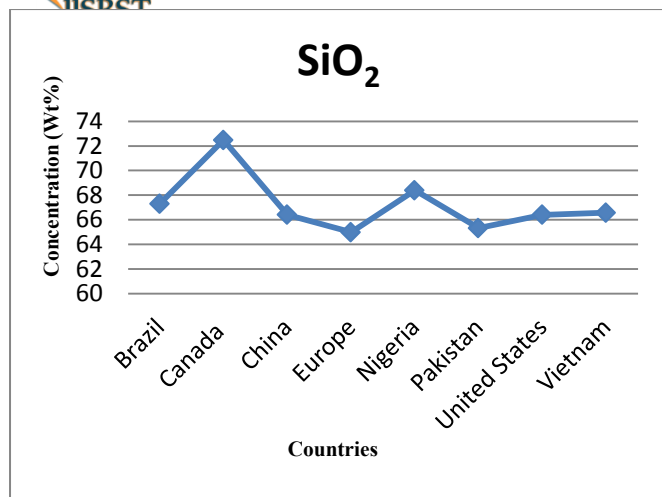
Countries ➡	Brazil		Canada				China
Oxides (Wt%)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
SiO ₂	67.3	65.41	63.11	67.65	62.39	72.48	66.41
TiO ₂	NA	NA	NA	NA	0.01	0.08	0.00
Al ₂ O ₃	18.2	16.48	11.63	17.48	13.19	18.18	18.19
FeO	0.37	0.11	5.03	0.83	3.33	NA	NA
Fe ₂ O ₃	NA	2.39	NA	NA	NA	1.32	NA
MnO	0.05	0.032	NA	NA	0.00	0.05	0.00
MgO	0.20	0.274	1.80	0.42	1.93	0.73	0.00
CaO	0.05	NA	NA	0.01	0.01	0.83	0.24
Na ₂ O	0.53	1.17	2.40	0.33	2.23	3.53	0.04
K ₂ O	NA	0.354	NA	0.06	0.00	3.31	0.04
Cr ₂ O ₃	NA	NA	NA	0.01	0.00	NA	
BeO	12.9	13.02	12.99	13.62	12.99	NA	13.29
Cs ₂ O	0.01	NA	NA	0.03	0.04	NA	NA
H ₂ O I	1.36	2.14	NA	NA	2.73	NA	NA

Table 3b.Continuation of table 3a

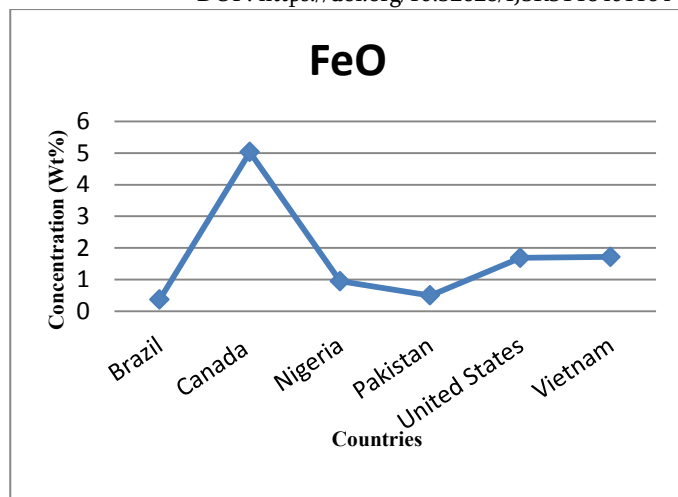
Countries →	Europe	Nigeria		Pakistan (Rim)	United States	Vietnam	
Oxides (Wt%)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
SiO ₂	64.99	65.17	66.10- 68.40	65.33	66.40	66.58	65.87
TiO ₂	NA	NA	<-0.02	0.07	0.01	0.00	NA
Al ₂ O ₃	17.17	18.84	18.02- 19.21	19.91	17.36	17.09	17.80
FeO	NA	0.46	0.11- 0.95	0.50	1.69	1.72	NA
Fe ₂ O ₃	0.97	NA	NA	NA	NA	NA	1.42
MnO	NA	NA	<-0.02	0.06	0.01	0.01	0.009
MgO	0.31	0.03	0.01- 0.20	0.11	0.04	0.12	0.058
CaO	NA	NA	<-0.01	0.48	0.00	0.00	0.030
Na ₂ O	1.08	0.10	0.04- 0.33	0.16	0.22	0.22	0.048
K ₂ O	0.29	NA	<-0.05	0.42	0.02	0.03	0.003
Cr ₂ O ₃	NA	0.01	<-0.05	0.00	0.00	0.01	NA
BeO	12.89	13.60	NA	NA	NA	13.79	13.52
Cs ₂ O	NA	NA	NA	NA	0.11	0.27	0.126

Note < Contents below detection limit; NA-Not available

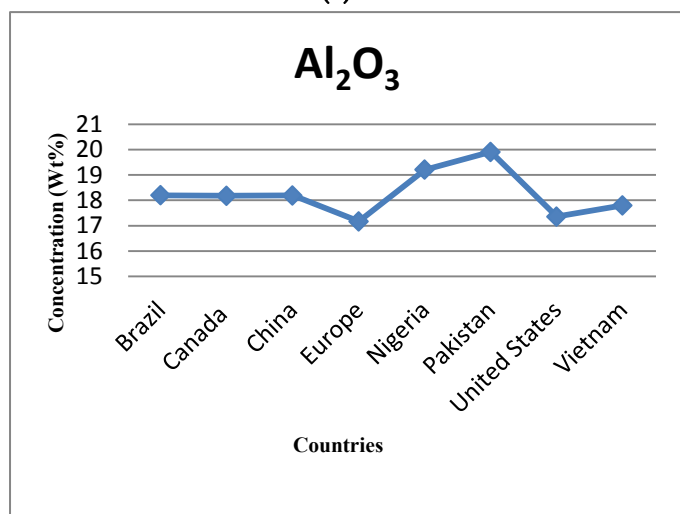
1- Minas gerais (Vianna et al., 2002); 2-Bahia State (Filho and Sighinolfi, 1973); 3- Canada (Adamo et al., 2008); 4- Zealand Station (Beal and Lentz, 2010); 5-Southern Yukon (Turner et al., 2007); 6- New Brunswick (Beal et al., 2010); 7- Hunan province (Zhaolin et al., 1994); 8-Switzerland (Mitchell et al., 2003); 9- Nigeria (Lind et al., 1986); 10- Central Nigeria (Schwarz et al., 1996); 11- Skardu, Gilgit-Baltistan (Agheem et al., 2014); 12- Colorado (Parkin et al., 1977); 13- ThanhHoa province (Fridrichova et al., 2014); 14-Thanh Goa Province (Huong et al., 2011)



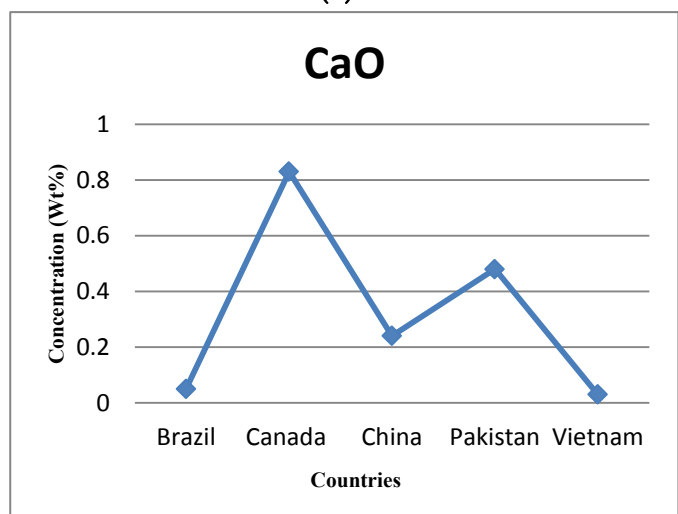
(a)



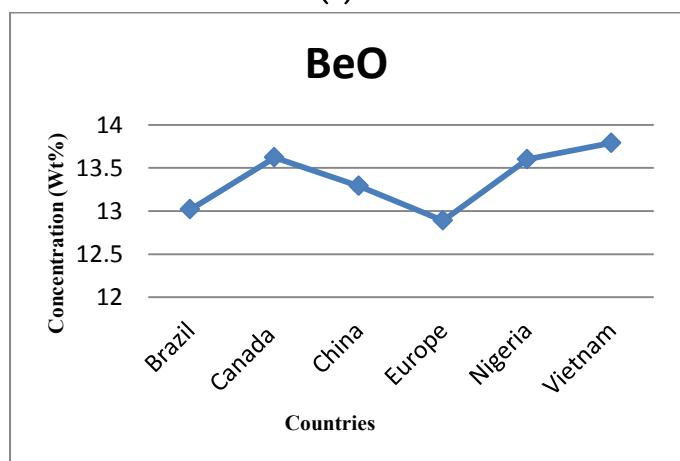
(d)



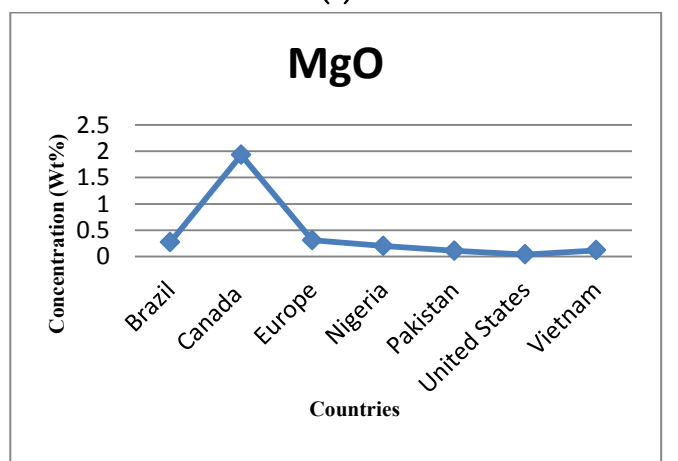
(b)



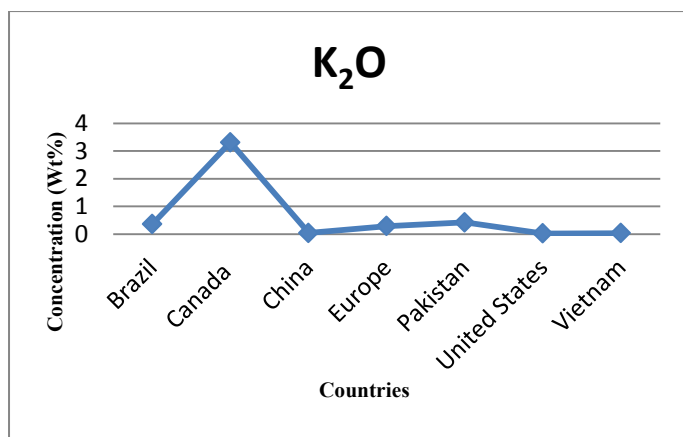
(e)



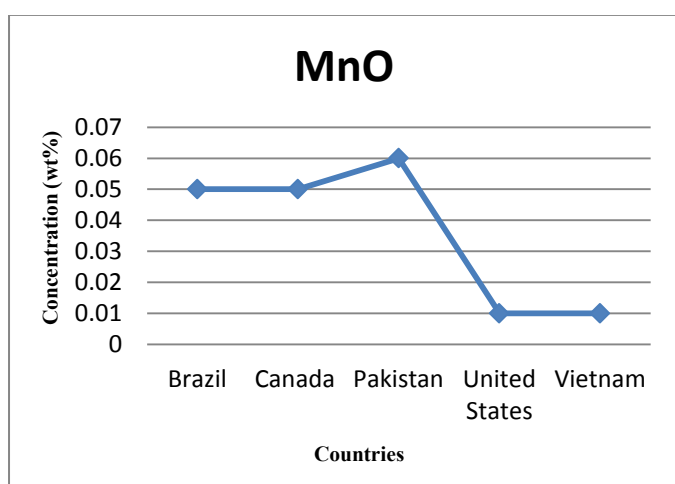
(c)



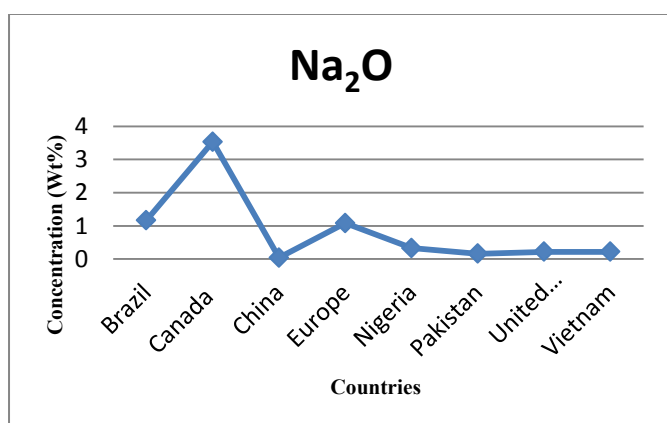
(f)



(g)



(h)



(i)

Fig. 3 Variation of oxides in Aquamarine

From tables 2a and 2b and Figures 3a to 3i, the minimum and maximum concentration observed and explained.

SiO₂ : It varies from 64.99 (Switzerland) to 72.48 (Canada).

Al₂O₃ : Minimum value is 11.63 (Canada) and the maximum is 19.91 (Pakistan).

BeO : Its percentage varies from 12.9 (Brazil) to 13.79 (Vietnam)

FeO : Lowest value 0.11 is noticed from Brazil, sample and the highest 5.03 from Canada.

CaO : Brazil sample contains the lowest 0.01 and the sample of Canada has 0.83.

MgO : It varies from 0.00 (China) to the highest 1.93 (Canada)

Na₂O : Maximum value (3.53) is observed in Canadian sample and Nigerian Aquamarine has 0.10 only.

K₂O : Nigerian and Vietnam samples show negligible quantities whereas sample f from Canada shows 3.31%.

MnO : It is present in very low concentrations i.e., from 0.00 (Canada and China) to 0.06 (Pakistan).

III. CONCLUSION

Aquamarine is an attracting bluish green color gemstone. It is occurring from few countries. Chemical analysis is also available from few countries only i.e., less than 10 countries. Chemical analysis indicated that the samples analyzed from the Canada show highest concentration of SiO₂, FeO, CaO, MgO, Na₂O and K₂O. Highest concentration of Al₂O₃, MnO is recorded in Pakistan sample and BeO in Vietnam. Lowest concentration of SiO₂ is recorded from Switzerland sample, Al₂O₃ and MnO from Canada, BeO, FeO and CaO from Brazil, MgO and MnO from China and Na₂O and K₂O from Nigeria samples.

IV. REFERENCES

- [1] Adamollaria, Alessandro Pavese, Loredana Prosperi, Valeria Diella, David Ajò, G. Diego Gatta, and Christopher P. Smith (2008) Aquamarine, Maxixe-Type Beryl, and Hydrothermal Synthetic Blue Beryl: Analysis and Identification, *Gems & Gemology*, Fall, 214-226
- [2] Agheem Muhammad Hassan, Mohammad Tahir Shah, Tahseenullah Khan, Mamoru Murata, Muhammad Arif and HumairaDars (2014) Shigar valley gemstones, their chemical composition and origin, *Skardu, Gilgit-Baltistan, Pakistan, Arab J Geosci* 7:3801–3814
- [3] Ahline Nicole and Maryam Mastery Salimi (2017) Mysterious Iridescence in Aquamarine, *Gems and Gemmology*, 53, 240-241
- [4] Badar M A, Safdar Hussain1, ShanawerNiaz, Saif Ur Rehman (2017) X-ray Diffraction Study of Aquamarine from Shigar Deposits, Skardu Valley, Northwest Pakistan, *Int. J. Econ. Environ. Geol.* 8 (4)33-40
- [5] Bank Francisco, Professor Hermann Bank and Elena Villa (2001) Santa Maria aquamarine, *The Journal of gemmology*, 27 (5) 257-258
- [6] Beal K.L, Lentz David R., Douglas C. Hall and Gregory Dunning (2010) Mineralogical, geochronological and geochemical characterization of Early Devonian Aquamarine bearing dykes of the Zealand Station beryl and molybdenite deposit, west central New Brunswick, *Can. J. Earth Sci.* 47:859-874
- [7] Lee B. K and David R. Lentz (2010) Aquamarine beryl from Zealand Station, Canada: a mineralogical and stable isotope study, *Journal of Geosciences*, 55, 57–67
- [8] Blak Ana Regina, SadaoIsotani and Shiguo Watanabe (1982) Optical Absorption and Electron Spin Resonance in Blue and Green Natural Beryl, *Phys. Chem Minerals*, 8 161-166
- [9] BocchioRosangela, IlariaAdamo, and Franca Caucia (2009) Aquamarine from the Masino-Bregaglia Massif, Central Alps, Italy, *Gems and Gemology*, Fall, 204-207
- [10] BunnagNantharat and Bhuwadol Wanthana chaisaeng (2014) Heat Treatment of Aquamarine, *The 4thInternational Gem and Jewelry Conference*, 97-100
- [11] Cairncross Bruce, Ian C. Campbell, And Jan Marten Huizenga (1998) Topaz, Aquamarine, And Other Beryls From Klein Spitzkoppe, Namibia, *Gems & Gemology*, Summer, 114-125
- [12] Cerny P and Hawthorne F. C(1976) Refractive Indices Versus Alkali Contents in Beryl: General Limitations and Applications to Some Pegmatitic Types, *Canadian Mineralogist*, 14, 491-497
- [13] ChankhanthaChawalit, Panjawan Thanasuthipitak (2012) Heat Treatment Of Aquamarine And Morganite From Madagascar, *38th Congress on Science and Technology of Thailand*.
- [14] ChoudaryGagan (2014) Aquamarine with unusually strong dichroism, *Gems and Gemology*, Fall, 244-245
- [15] DanetFabrice, Marie Schoor, Jean-Claude Boulliard, Daniel R. Neuville, Olivier Beyssac, and Vincent Bourgoïn (2012) Inclusions in Aquamarine from Ambato fotsikely, Madagascar, *Gems and Gemology*, Fall, 205-208
- [16] Danner J. M. Duroc-(1989) Medium-dark blue aquamarines from Tongafeno, Madagascar, with high physical and optical properties, and showing three-phase inclusions, *J. Gemm.*, 21(7) 423-430
- [17] Figueiredo M. O., Pereira Da Silva T., J. P. Veiga, C. Leal Gomes And V. De Andrade (2008) The Blue Colouring Of Beryls From Licungo, Mozambique: An X-Ray Absorption Spectroscopy Study At The Iron K-Edge, *Mineralogical Magazine*, February 2008, 72(1), 175–178

- [18] Filho H.de Almeida Sampaio and Sighinolfi G.P. (1973) Contribution to the Crystal Chemistry of Beryl, *Contr. Mineral. and Petrol.* 38, 279-290
- [19] Francis Carl A., Myles Felch, Alexander U. Falster & Douglas A. Bailey(2016) Aquamarine from Stoneham and Vicinity, Oxford County, Maine, *Rocks & Minerals*, 91:1, 28-35
- [20] Fridrichová Jana, Peter Bac'ík, Petra Rusinová, Peter Antal, RadekŠkoda, ValériaBizovská, Marcel Miglierini (2015) Optical and crystal-chemical changes in Aquamarines and yellow beryls from Thanh Hoa province, Vietnam induced by heat treatment, *Phys. Chem Minerals* 42:287–302
- [21] Gerasimova E. I., Vigasina M. F., Prokofiev V. Yu., Nagornaya E. V (2014) Inclusions in Aquamarine from the Suprunovskoye Pegmatite Deposit, Russia, *ActaGeologicaSinica* (English Edition), 88(supp. 2): 1094
- [22] Groat Lee A., George R. Rossman, M. Darby Dyar, David Turner, Paula M.B. Piccoli And Arthurj. Schultz, Luisa Ottolini (2010) Crystal Chemistry Of Dark Blue Aquamarine From The True Blue Showing, Yukon Territory, Canada, *The Canadian Mineralogist* 48, 597-613
- [23] GroatLee.A, Craig J.R. Hart, Lara L. Lewis, and Heather L.D.Neufeld (2005) Emerald and Aquamarine Mineralization in Canada, *Geoscience Canada*, 32 (2), 65-76
- [24] Huong Le Thi-Thu, Tobias Häger, Wolfgang Hofmeister, ChristophHauzenberger, Dietmar Schwarz, Pham Van Long, Ursula Wehmeister, Nguyen Ngoc Khoi, and NguyTuyetNhung (2012) Gemstones From Vietnam: An Update, *Gems And Gemology*, Fall, 168-170
- [25] Huong Le Thi-Thu, Wolfgang Hofmeister, Tobias Häger, Nguyen Ngoc Khoi, NguyTuyetNhung, WilawanAtichat, and VisutPisutha-Arnond (2011) Aquamarine from the thuongXuan District, ThanhHoa Province, Vietnam, *Gems & Gemology Spring*, 42-48
- [26] IYER, L A. N. (1961). *Indian Precious Stones.*, Bulletin Geological Survey of India, 18,89
- [27] Jacobson Mark I. (1993) Aquamarine in the United States, *Rocks & Minerals*, 68:5, 306-319
- [28] Kane Robert E.(1985) BERYL, Bicolor, gems and Gemology, 21, 232
- [29] Kim Sungjae and Dong wook Shin (2014) Aquamarine from the GilgitBaltistan of Northern Areas, Pakistan, *The 4thInternational Gem and Jewelry Conference*, 149-152
- [30] Koivula John I. and Robert C. Katnmerling (1989) Fine Aquamarine from India, *Gems and Gemology*, Fall, 179-180
- [31] Laurs Brendan M., Brendan M. and Alexander U Falster(2012) New gem discoveries in Ethiopia. file:///C:/Users/SANKAR/Downloads/newgemdiscoveriesinethiopia.pdf
- [32] Lind T., K. Schmetzer and H. Bankt (1986) Blue and green beryls (Aquamarines and emeralds) of gem quality from Nigeria, *Journal of gemology*, 20, 1
- [33] Linnen Robert L., David Turner, and Lee A. Groat (2006) A Fluid Inclusion Study of the Syenite-Hosted “True Blue” Aquamarine Occurrence, Yukon Territory, Canada, *Gems and Gemology*, 42, 114
- [34] Lum, J., Viljoen, F., Cairncross, B., Frei, D.,(2016) Mineralogical and geochemical characteristics of Beryl (Aquamarine) from the Erongo Volcanic Complex, Namibia, *Journal of African Earth Sciences*, doi: 10.1016/j.jafrearsci.2016.09.006
- [35] M1shra, B. P. And Mohanty, B. K. (1995) *Geology and Mineral Resources of Orissa.* Society of Geoscientist and Allied Technologists, 185-202
- [36] Mathew George (1998) *Mineralogical Studies On The Gem Varieties Of Beryl From Orissa, India*, Thesis submitted to The Maharaja Sayajirao University Of Baroda

- [37] Mitchell G. Mihalyanuk and Ray Lett (2003) Composition of Longtung Beryl (Aquamarine) by ICPE/MS: A Comparison with Beryl Worldwide, British Columbia Geological Survey, Geological Fieldwork.
- [38] Muntyan B L (2013) The Rediscovery of Long-Lost Aquamarine from The Sierrita Mountains, Arizona, *Rocks & Minerals*, 88:3, 222-230
- [39] Nassa K (1996) On the identification and fade testing of Maxixe beryl, golden beryl and green aquamarine, *Journal of Gemmology.*, 1996, 25, 2. 108-115
- [40] Nassau K and Wood D.L (1973) Examination of Maxixe-type Blue and Green Beryl, *Gems and Gemology*, Spring, 130-133
- [41] Nassau Kurt, Betty E. Prescott and D.L Wood (1976) The deep blue Maxixe-type color center in beryl, *American Mineralogist*, 61, 100-107
- [42] Nikbakht T, Kakuee O and Lamehi-Rachti M (2016) Study of Ionoluminescence behavior of the gemstones: Beryl (aquamarine variety), Opal and Topaz, *Journal of Luminescence* 171, 154-158
- [43] Ostrooumov M. (2016) Aquamarine from a new primary deposit in Mexico, *Gems and Gemology*, Fall, 317-318
- [44] Panjikar Jayashree and Aatish Panjikar (2014) Aquamarine from Karur, Tamil Nadu India, The 4th international Gem and Jewelry Conference, 145-148
- [45] Parkin K.M, Bruce M. Loeffler and Roger G. Burns (1977) Mossbauer Spectra of Kyanite, Aquamarine and Cordierite Showing Intervalence Charge Transfer, *Physc. Chem. Minerals* 1, 301-311
- [46] Proctor Keith (1984) Gem Pegmatites of Minas Gerais, Brazil: Exploration, Occurrence and Aquamarine Deposits, *Gems & Gemology*, Summer, 78-99
- [47] Ruzeng Yang, Xu Hongyi and Li Minjie (2007) The effect of heat treatment on colour, quality and inclusions of aquamarine from China, *The Journal of Gemmology*, 30, 5 /6, 297-301
- [48] Schwarz Dietmar, Jan Kanis² and Dr Judith Kinnaird (1996) Emerald and green beryl from Central Nigeria, *J. Gemm.*, 25, 2, 117-141
- [49] Spinolo G., I. Fontana, and A. Galli (2007) Optical absorption spectra of Fe²⁺ and Fe³⁺ in beryl crystals, *phys. stat. sol. (b)* 244, 12, 4660-4668
- [50] Turner David, Lee A. Groat. Craig J.R. Hart, James K. Mortensen, Robert L. Linnen, Gaston Giuliani, William Wengzynowski (2007) Mineralogical And Geochemical Study Of The True Blue Aquamarine Showing, Southern Yukon, *The Canadian Mineralogist*, 45, 203-227
- [51] UNDP Technical Report (1983). Mineral Exploration and Development in Kerala., : UNDP, New York, 42
- [52] Viana R.R, H. Jordt-Evangelista G. Magela da Costa and W. B. Stern (2002) Characterization of beryl (Aquamarine variety) from pegmatites of Minas Gerais, Brazil, *PhysChem Minerals* 29: 668 – 679
- [53] Watters W. A. (2014) Zoned blue beryl from the Canaan area, Pikikiruna range, Nelson, New Zealand *Journal of Geology and Geophysics*, 6:5, 715-717
- [54] Yang Hu and Ren Lu (2018) Aquamarine from Pakistan, *Gems and Gemmology*, Spring, LIV, 98-101
- [55] Zhaolin Li, Yanhua Mao, Lihong Lei, Zhili Qiu, and Hecai Niu (1994) Physicochemical conditions of the formation of Beryl and Aquamarine in Mufushan Granopegmatite deposit, Hunan Province, china, *Chineser journal of Geochemistry*, 13,4, 326-339
- [56] <http://www.geologyin.com/2017/05/the-different-beryl-varieties-with.html>
- [57] <https://commons.wikimedia.org/wiki/File:Beryl-209736.jpg>