ADDIS ABABA UNIVERSITY
COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES
SCHOOL OF EARTH SCIENCES

THE KILKILE EMERALD; GENESIS, MINERALOGY, CHEMISTRY AND MINING; KILKILE, SHAKISO- SOUTHERN ETHIOPIA

BY
GIRMA ABERA YILMA
GSR/4566/09

"A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE (MSc) IN RESOURCE GEOLOGY, MINING GEOLOGY, IN THE SCHOOL OF EARTH SCIENCES OF ADDIS ABABA UNIVERSITY."

SEPTEMBER, 2019

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Declaration

"This Thesis is my original work and has not been presented for a Degree in any other University."

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Abstract

This study provides quantitative geochemical, petrological, and mineralogical data on major rock types and emeralds of the kilkile area. The meta-basic rocks containing 740ppm Cr provided the amount necessary for emerald mineralization. Emerald-hosting biotite schist is confined to the contacts of quartz- feldspar- muscovite pegmatite dykes/veins with meta-basics. The pegmatite dykes are genetically related to a fertile granite pluton within the Adola district. The formation of biotite schist from meta-basic rocks is associated with the introduction of pegmatitic components in to the meta-basics, causing enrichment with the pegmatitic composition. Quartz-feldspar-muscovite pegmatites of the kilkile area belongs to the rare-element pegmatites of the LCT family with common beryllium enrichment (12ppm). These pegmatite dykes/veins intruded the N-S orienting regional structures. The emeralds have higher MgO (0.26-4.08 wt. %), Fe_2O_3 (1.39-2.18 wt. %), Al_2O_3 (17.7- 20.1 wt. %), CaO (1.25-3.85 wt. %), K_2O (0.07-1.7 wt. %), P_2O_5 (0.02-1.88) and Be (527-1000 ppm) and lower Cr_2O_3 (0.01-0.09 wt. %) and SiO_2 (59.13-61.79 wt. %) contents. The relatively higher value of iron and magnesium in the kilkile emerald might attribute for the ferromagnesian nature of the meta-basic rocks or aggressiveness of the brine solution in liberating Mg and Fe from meta-basic rocks. The low chromium content in the meta-basic rocks contribute for chromium deficiency in the emerald. The high value of Fe_2O_3 depresses the green colour in addition to low Cr_2O_3. Compared to the Zambian, the meta-basic rocks in the case of Ethiopia have low magnesium and iron content. However, the relatively higher value of iron and magnesium in Ethiopian emerald might contribute for relative competency of magnesium and iron in occupying the aluminium site in the crystal structure of beryl. The higher value of K_2O in the Ethiopian emeralds than in Zambian might suggest the role of potassium metasomatism at the pegmatite and meta-basic contact. The genesis of Ethiopian emerald holds the classical model for emerald mineralization, the condition in which pegmatites interact with the surrounding meta-basic rocks. The current mining activity at kilkile area requires vertical to horizontal ratio chances due to the overlapping of mining progress with direction with the dipping of the host rock units. Therefore, low vertical to horizontal ratio is recommended for the western berms of the mining pits.

CHAPTER ONE

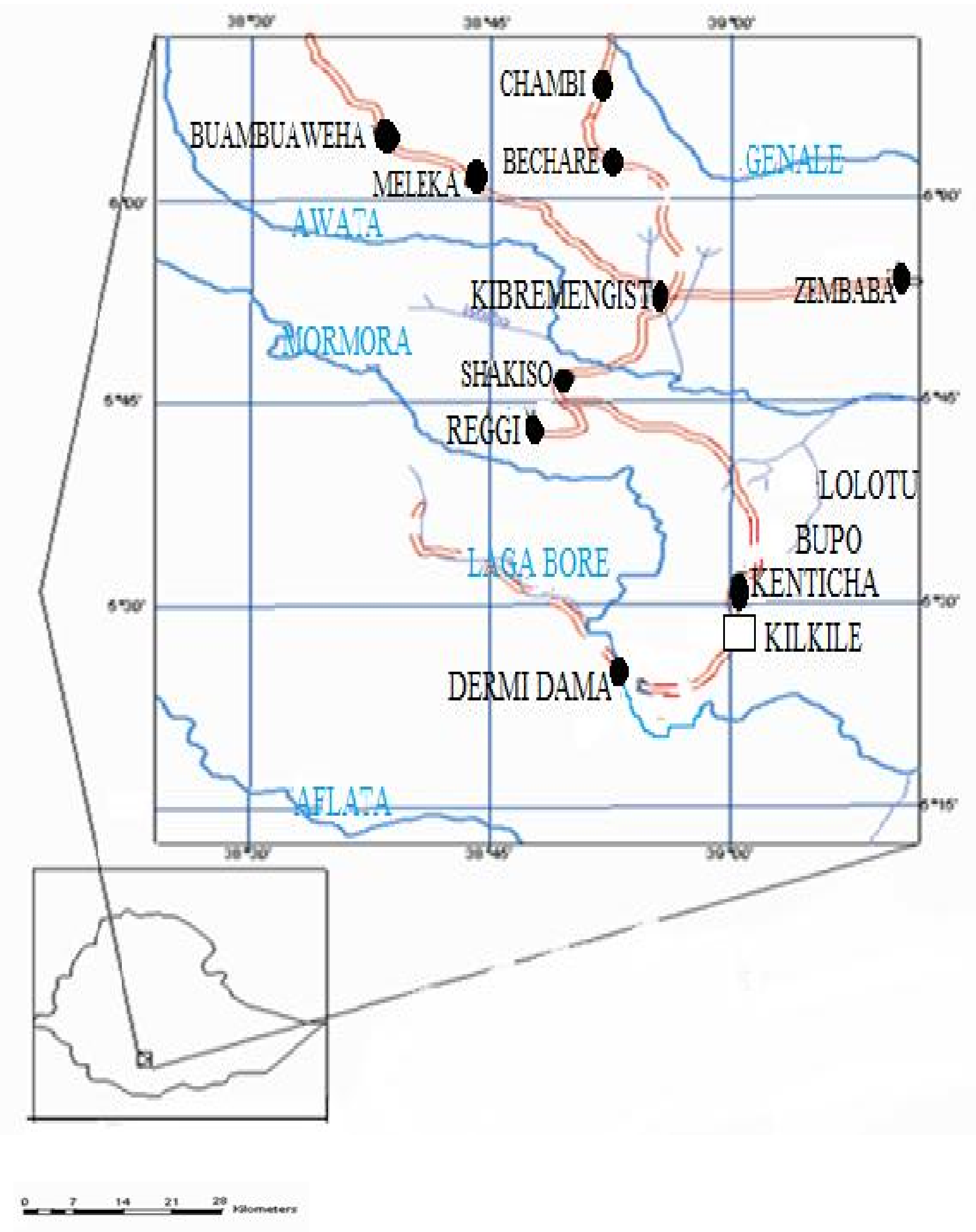
1 INTRODUCTION

1.1 Background Information

Ethiopia has a diverse and interesting geology with proven mineral and gemstone deposits**.** To date, the new emerald deposit at Kilkile area of the Saba Boru district (figure 1.1) have yielded 300kg (1.5% of the global market) of mixed-grade rough. Approximately 5% of this can be cut into gems, producing 3.8kg (19,000 carats) of faceted stones. Emerald mining in Ethiopia is relatively small-scale but yields gem-quality crystal material that can be faceted into exquisitely fine, clean and unique emeralds that are comparable to those mined from Chivor in Colombia. There have been small-scale artisanal mines yielding some high-quality emeralds since 2004 but new, larger deposits were discovered by local farmers in 2015. Initially, small parcels of rough Ethiopian emerald were presented in the European markets and at gem shows in the USA in early 2016 but with limited interest; the quality of the rough was very low. However, new parcels emerged with glimpses of gem quality rough later. Mining output improved but, with absence of machineries, still remained to be 20kg per month of mixed grade material. Prices of Ethiopian rough emeralds jumped throughout 2017 and, since the relatively low yield from the mines, supply was scarce. Buyers were offered mixed parcels only (no selection allowed) and these contained large low grade and commercial grade pieces of rough mixed with a few pieces of gem-quality material. The low-grade emeralds had little commercial value and are often fractured and heavily included with black mica. Therefore, the cost per gem-quality piece of rough increased and exceeded levels of even Zambian rough. After cutting and polishing these rough emeralds, many of the small scale buyers and wholesalers would, disappointingly, disguise the origin, often pushing for Zambian origin certification as it is similar in appearance and more established in the market. The research program entitled *"THE KILKILE EMERALD; GENESIS, MINERALOGY, CHEMISTRY AND MINING; KILKILE, SHAKISO- SOUTHERN ETHIOPIA"* entailed petrological, geochemical and mineralogical conditions of the major rocks and minerals of the Kilkile area. The major objective was the study of the origin and distribution of the emerald mineralization and proposing method/s of mining for it. During the fieldwork; all field data including structural data on the quartz-apatite-beryl veins, meta-basics, pegmatites and the exact GPS positioning of documented points have been recorded on digitalized topographic map sheets at 1: 250,000 scale. Altogether 21 rock and mineral samples were studied for their mineralogical and geochemical composition analyses. The results of the analyses of these samples and the interpretation of data constitute the main parts of this document. The topographic materials used include; topographic map at 1: 250,000 scale, a geological map of the Adola area at 1: 100,000 scale and different reports on emerald potential of the Kilkile area by Geological Survey of Ethiopia. For many years the Adola, Shakiso and Kilkile restricted area have been subdivided into a large number of prospecting plots as a result of the enormous interest in mineral exploration. This was done without the benefit of a thorough geological evaluation, the consideration of favorable indicators, or modern prospecting and exploration techniques particularly in terms of gemstone at Kilkile area. The main production is currently limited to minor artisanal and very few semi-mechanized mining.

1.2 Location and accessibility of the study area

The study area is located in Southern Ethiopia, Oromia National Regional State, Eastern Guji Zone, Dermi Dama Woreda, Saba Boru District, Kilkile local area. Areal coverage of the area is about 7.5Km^2 bounded by 503000-505125 East Longitude and 598000-601535 North Latitude. The study area can be reached using air flight from Addis Ababa up to Shakiso town for 500Km followed by four wheel drive vehicle from Shakiso to Kilkile for the remaining 50Km. The main highway from the capital, Addis Ababa to Shakiso passes through Addis Ababa-Modjo-Shashamane-Hawassa-Shakiso. From Addis Ababa to Shakiso it can be accessed through asphalt road whereas from Shakiso to Kilkile, it is all weather gravel road. Footpaths connecting villages are common in the mapping area, which are very important in facilitating to get back to villages from field travels.



LEGENDS

Locality

All weathered gravel road

Dry weathered road

Stream

REFERANCE SYSTEM: UTM 37

ELLIPSOID: ADINDAN (30th arc)

Figure 1.1 Location map of the study area

1.3 Physiography and climate of the study area

The Kilkile area is characterized by a typically mountainous topography that is highly rugged and sloppy with absolute elevations ranging from 1500m to 1900m A.S.L. The mountain slopes are dissected by a dense network of deeply incised minor creek valleys of the Mormora drainage area. It lies in the interface area between Awata and Mormora rivers. The Mormora river is the largest perennial river in the area. The drainage of the study area forms well developed dendritic pattern. The climate of the study area is equatorial monsoon type that includes both hot and humid conditions and it accompanied by abrupt change of dry and rainy seasons respectively. The main rainy seasons are two, from March to May and September to November. The remaining months are generally characterized by dry weather conditions. The mean annual precipitation ranges from 1100mm to 1300mm with daily average temperature ranges from 11^0C to 13^0C minimum and 24^0C to 30^0C maximum.

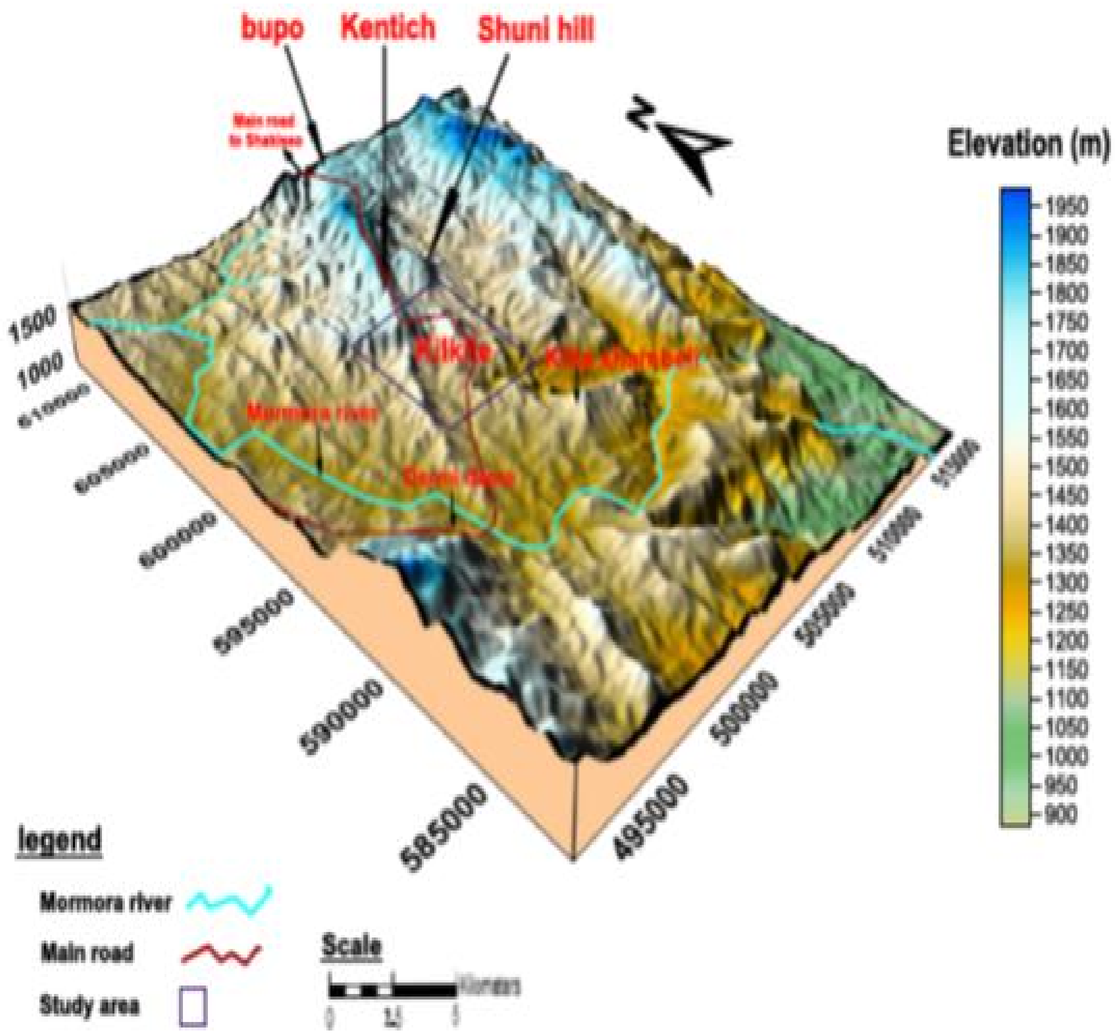


Figure 1.2 Physiographic map of the study area

1.4 Objectives of the study

1.4.1 General objective

"The general objective of this study is establishing the role of different geological and geochemical events in the genesis of Kilkile emerald and proposing best method/s of mining for it."

1.4.2 Specific objectives

The specific objectives of the proposed study are the followings:-

- ❖ To identify the host rock and sought mineral relationships
- ❖ To establish genetic classification for the Kilkile emerald
- ❖ To establish best method/s of mining for the Kilkile emerald
- ❖ To establish major similarities and differences among Kilkile emerald and its Zambian counterpart.

1.5 Purpose of the study

As it has been already described in the introductory portion of this chapter, the global market disguise for Ethiopian emerald is due to the lack of established class for it. Mode of formation, gemmological properties, chemical and physico-mechanical studies can distinguish between Ethiopian and its counterpart; Zambian emerald. Therefore, in the recent study, chemical analyses in terms of major, minor and trace element and base metal concentration of the host and source rocks, emerald and associated minerals have been used to distinguish between Ethiopian and Zambian emerald. This enables the appointment of Ethiopian emerald as a unique category of itself. Additionally, there are a number of genetic classification schemes for emerald mineralization of different countries for which Ethiopian emerald is not yet described. Therefore; **"**The findings of the research will be helpful in- establishing the class and proposing method/s of mining for the betterment of pricing and supply for Ethiopian Kilkile emerald."

1.6 Methodologies

To meet my objectives from the very beginning; different methods will be followed. The overall activities aimed to achieve the mentioned objectives of the study can be grouped in to three phases; pre-field work, field work and post-field work. The pre-field work phase comprises activities conducted before the actual field work. The phase starts from psychological make-up and extended to journey to Kilkile for the actual field work. The field work phase consists of activities handled during the actual field work at Kilkile. This phase constructs the major input to the study since almost all primary data for the study comes through this phase of work. Finally, the third phase; post-field work phase consists of processing and presentation of the inputs obtained during pre-field and actual field work phases. All of the above mentioned phases have incorporated different activities, procedures and instrumentations to attain their sought requirements. Methodologies that have been incorporated in each of the above mentioned phases of activities would be grouped in to three; data collection, data analysis and synthesis and data presentation and interpretation.

1.6.1 Data collection

The performed study inquired two data sources; secondary and primary data. These data have been collected during pre and actual field work phases of activities mentioned above. Prior to secondary and primary data collection, different permit and collaboration letters have been prepared and presented to the concerned organizations, offices and personnel. Once the permit and collaboration letters have got acceptance and go ahead letters from concerned offices have been received, the collection of the two data undertook in a separate phases; pre-field and actual field work phases.

1.6.1.1 Pre-field work

During the pre-field work phase; the activities undertaken includes the followings:-

- ✓ Literature reviews of different works done in the proposed study area and similar areas elsewhere to broaden the researcher thinking to undergo the overall research work starting from selecting study area, methodology and deciding the objectives.
- ✓ Pre-field visit to enhance the information obtained on the accessibility, supply, operational and technical assemblages of the mining activities in the proposed study area.
- ✓ Secondary data collection and confirmations of availabilities of laboratory and technical inputs required for the proposed study in different organizations and authorities.
- ✓ Internet browsing to gate information up to date on emerald mining elsewhere in the world to correlate with the existing mining procedures in the proposed study area.
- ✓ Temporary research title submission and advisor nomination by the researcher and timely contact with the nominee on the submitted title and proposal writing.
- ✓ Research proposal preparation, submission and presentation to the School of Earth Sciences of Addis Ababa University.

1.6.1.2 Actual field work

Once the proposal has got permission and approval, the primary data collection have been followed during the next phase; the actual field work phase. The activities that have been conducted during primary data collection were the followings:-

- Preparation of field equipment, facilities and supporting stuffs
- Fixing the working hours, sampling stations, spacing, volume, orientation and population. Accordingly, about three rough emerald, one apatite, three quartz-apatite-beryl and fourteen representative rock samples were systematically collected for petrographic, geochemical and geotechnical studies from some appropriate locations. Throughout all traverses photos are taken for all mineralogical, lithological and structural elements by digital camera to facilitate the whole thesis.
- Collecting mineralogical, lithological, structural, and geotechnical data, following predetermined traverse lines and spacing.

The traverses were designed across the structure and mineralogical alterations or zonings and denser traverse lines and observation points were taken where the exposure of the mineralization are clear and abundant. Accordingly fifteen traverse lines were selected that potentially targeting to cross the structures and/or mineralogical alterations or zonings. Observation points were made depending on the changes in the lithological, structural and mineralogical complexity. In the field; different rock formations and their relationship to the other formations were observed. Lithological, mineralogical and structural descriptions- variation in color, texture, mineral composition, zoning, alteration, kind and degree of weathering, color of fresh surface, fabric and many more have been made.

In relation to measurements; observation and recording of all structural data- joints, veins, faults, folds etc. have been undertaken. Descriptions of all lithological units and interpretations of rocks and minerals was mainly done on site by visual observation using hand lenses. Once the data were collected in the above mentioned two phases; the next phase was the post-field work phase. Activities incorporated in this phase were data analysis, synthesis, presentation and interpretation

1.6.2 Data analysis and synthesis

1.6.2.1 Data analysis

After collecting data; the next work was to analyze those relevant data obtained during data collection. The analysis was done in laboratory on the samples collected during actual field work. Laboratory analyses were aimed for three major purposes- mineralogical, geochemical and geotechnical examinations.

1.6.2.1.1 Samples for geochemical examinations

Geochemical samples have been used for compositional examinations of Ethiopian emerald. The sample preparation for geochemical analysis was to make the sample in a powder form. To do this, three steps have been followed; break the sample in to desirable sizes in confined container not to lose the fines, crush the broken sample in a crusher and finally the crushed sample will be milled in automatic milling machine. Then; we check the grain size of the powder for it is in clay size (200 mesh=75 μm) when the milling process is finished (usually after every 30 minutes). After checking; if the powder is above clay size, we need to re-mill it. But, if the powder is in clay size it's good to go to the final stage; packing and labeling. The same process have been applied for the other samples. Finally, after all samples are finished, the samples were sent to abroad laboratory for chemical analysis for all constituent oxides and elements. Major element analyses were performed by X-Ray Fluorescence (XRF). Minor, trace and Rare Earth Element analyses were performed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Base metals analyses were performed by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES).

1.6.2.1.2 Samples for geotechnical examinations

Samples for geotechnical examinations were collected to propose mining method/s to be followed in the area. Rock mass ratings have been conducted based on field measurements and compressive strength test on the collected samples.

1.6.2.2 Data synthesis

The analyzed data, then have been synthesized in to a useful information to assist interpretation. The laboratory chemical analysis, lithological, structural and geotechnical data have been synthesized using software such as Microsoft Excel, ArcGIS, Microsoft Paint and Dips.exe. The synthesized data would have been utilized during interpretation of results showing all the necessary information about mineralogical characteristics, chemical compositions and geotechnical makeups of emerald mineralization.

1.6.3 Data presentation and interpretation

The data collected by means of exempting from previously collected sources or fieldwork once analyzed and synthesized as explained on above; have been presented and interpreted. The presentation was mainly of the mineralogical, geochemical, lithological, geotechnical and mining descriptions by either of four means (texts, tables, graphs and diagrams). The presented data have been interpreted by comparing with the mining procedure at Kilkile area, up to date emerald mining procedures and taking in considerations of important literatures that follow similar methodologies. After these all works; the final thesis report have been compiled by organizing literature reviews, secondary and primary data (mineralogical, geochemical, lithological and geotechnical) analyses results.

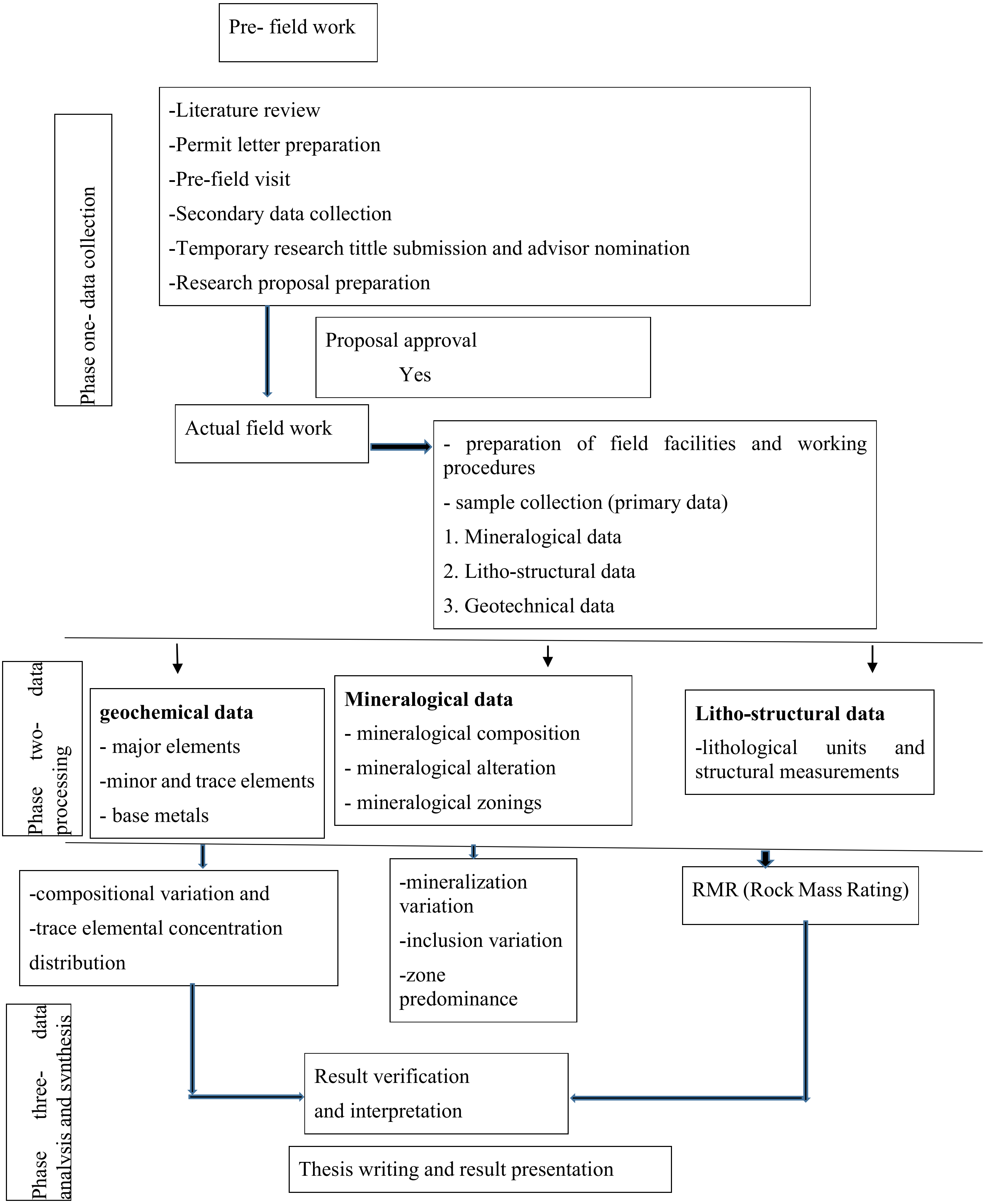


Figure 1.3 Schematics of methodologies

1.7 Literature reviews

Gems are wrought into the history and literature of nearly all peoples, and furnish standards of color, hardness, luster, and, for the most part, transparency. It is generally essential that a mineral to be a gem should excel in at least three of the above mentioned properties, although a few are superior in only two (Farrington, 1903). Advances in civilization seem to increase rather than diminish the number of minerals used as gems, the number now employed being larger than ever before in the world's history. While it is true that the qualities which have been prized in gems, and the relative esteem in which they have been held, seem to have been much the same in all ages, the fashion in gems may vary from time to time, so that now one stone and now another may take on temporarily a higher value. Yet, on the whole, their worth varies little among different peoples and at different times. The principal exception to this rule is found in the valuation of jade by the Chinese, for they esteem this above all other precious. Aside from a few such exceptions, gems pass current in nearly all countries at about the same value. They hence afford to a certain extent a medium of exchange, and are often made objects of investment, because they are small, portable, and have intrinsic value. It is not likely that any great excess or diminution of supply will occur to change the value of the leading gems, such as diamond, ruby, sapphire, and emerald, as they seem to be distributed in the earth's crust in but sparing amount. Among the less valuable gems, great variations in value have occurred, and may again. The elements entering into the chemical composition of gems are not as a rule themselves rare. They are chiefly silicon, aluminum, magnesium, and other common elements, usually combined with oxygen, and all abundant constituents of the earth's crust. It is thus not the rarity of their elements which gives gems their high value, but rather their peculiar properties as compounds. The formation of gems require source rocks, transporting agents, passageways and deposition sites for their economic concentration.

Pegmatites are sources of gem-quality crystals of beryl, tourmaline, topaz, spodumene, and spessartine. Most high-quality gem minerals occur in miarolitic cavities found near the centers of pegmatite bodies or in reaction zones between pegmatites and ultramafic host rocks. Single, spectacular miarolitic cavities in some pegmatites have produced tons of gem crystals valued in excess of $50 million (Simmons et al., 2012). The most important gem-bearing granitic pegmatites formed at shallow levels in the continental crust during the latest stages of collisional plate tectonic events. All significant gem-bearing pegmatites are granitic in composition. Only rarely do pegmatite bodies of mafic or alkaline compositions (e.g. Gabbro, nepheline, and syenite) contain gem minerals, such as microcline (amazonite), sodalite, and zircon. Six gem forming processes have been identified based on source rocks, fluids, temperature and pressure of their formation (Simmons et al., 2012).

A) Low temperature, involving surface and ground water near ambient temperature, dissolution, leaching and precipitation processes resulted gems. Carbonic acid (HCO_3) from rainwater dissolves and leaches limestone. The leachates carry metal cations (often from adjacent volcanic rocks) to precipitate: Malachite ($CuCO_3$) Rhodochrosite ($MnCO_3$) Turquoise ($CuAl_6$ (PO_4) $(OH)_8$. Sulfuric acid (H_2SO_4) formed by reaction of rainwater or groundwater with pyrite (FeS_2) acts to leach and dissolve many oxide minerals and transport metals to form supergene ore deposits and some gem minerals. Sandstone or silica-rich volcanic rocks need great long term and seasonal fluctuation. Silica carried in solution by groundwater until evaporation causes supersaturation of groundwater with silica. Silica then precipitates within cavities in the rock as silica-gel, semisolid spheres of SiO2*nH2O. With time and further evaporation, gel hardens to form opal. Opal forms in arid regions underlain by quartz.

B) Heated groundwater, low temperature hydrothermal processes resulted gems. Same as above but heat allows groundwater/acids to become more reactive and convectively circulate.

Nearly all agates form this way, as does most of the world's amethyst, in silica-rich volcanic host rocks that provide both a source and a site for silica dissolution and precipitation.

C) Heated groundwater, magmatic water, high temperature hydrothermal processes (hot springs analog) resulted gems. Hydrothermal veins (50-500^oC) form from hot, mineral-rich, solutions that escape from a cooling body of magma and mix with convecting Ground water can transport large quantities of silica to produce quartz veins and transport volatile elements (Be, F, Cl, etc.) that originate in magma. Fluids can hydrofracture surrounding rock, creating their own pathways. Cooler temperatures and drop in pressure leads to precipitation of emerald, Amethyst, imperial topaz, some base and precious metals, characteristically vein deposits.

D) Pegmatites (very coarse-grained intrusive rock that forms during the late stages of crystallization of larger masses of magma) resulted gems. Granite magmas are most important and source for unique gems. They are source of large and clean crystals due to slow rate of crystallization, high fluid content and high concentrations of rare elements like Be, Li, B, Mn, P, F leading to formation of aquamarine, tourmaline, chrysoberyl, topaz, Mn-garnet, kunzite

E) Volcanogenic processes resulted gems. In volcanogenic processes constituents essentially crystallize from cooling lava or precipitate from gas cavities. Gas cavity precipitates crystallize in gas pockets in cooling lava. Peridot, moonstone, topaz, some chalcedony (agate) from through these processes. Crystals that formed in a magma at great depth (entrained crystals) and were carried to the surface by erupting lava or kimberlite are source of gems like Peridot, zircon, sapphire, diamond and some garnet.

F) Metamorphic processes resulted gems. Process requires elevated temperature and pressures, but does not involve melting of rock. Transformation of limestone into marble, sandstone into quartzite, mudstone into schist or gneiss, serpentine into jade involves formation of ruby, garnets spinel, sapphire and alexandrite, tanzanite, aventurine and jade.

As far as sites of depositions are concerned, Simmons et al. (2012) proposed three sites of economic gem quality crystals formation (deposition):-

A) Crystals frozen in massive quartz or feldspar in the core or core margin of a pegmatite. Aquamarine (green blue to blue beryl variety) and tourmaline commonly occur in massive quartz or feldspar of the centrally located pegmatite core zone or in the core margin, the region around the core. Typically, only parts of these crystals are of gem quality, and gemstock is recovered by breaking out clear portions from the crystals.

B) Crystals in reaction zones surrounding pegmatites that intrude mafic rocks. Gems formed at the contact of pegmatitic dykes/veins with mafic country rocks. Emerald (the grass green, Cr- or Cr–V-rich variety of beryl) and alexandrite (the Cr- or Cr–V-rich variety of chrysoberyl) in Urals-type deposits, such as those in the Ural Mountains of Russia, the Kafubu area of Zambia, and the Mananjary area of Madagascar are typical examples.

C) Crystals in miarolitic cavities (also known as pockets). Miarolitic cavities form in residual melts that have accumulated via fractional crystallization with or without constitutional zone refining (London and Morgan, 2012; Jahns and Burnham, 1969). The gem varieties of beryl (aquamarine, heliodor and morganite), spessartine, spodumene (kunzite, hiddenite), topaz, and tourmaline (indicolite, rubellite, verdelite, liddicoatite, etc.) occur almost exclusively in miarolitic cavities (open or clay filled voids) in the cores of pegmatites; they may also occur in cavities in the coarse interior units surrounding quartz rich cores (the core-margin zone). Gem-bearing pockets represent the ultimate concentrations of exotic elements, volatiles, and other fluxes present in pegmatites. They contain the most evolved assemblage of gem-quality minerals and associated rare Nb–Ta–Sn oxides, phosphates, fluorides, borates and borosilicates. The high value of gem material makes these pegmatites highly sought. However, cavities containing gem-quality crystals are very rare. Most pegmatite mines only produce high-quality gem minerals sporadically and thus cannot be operated economically.

Beryl is often associated with granitic intrusives that carry fluxing agents (boron, fluorine, phosphorus). Such magma is less viscous, persists to lower temperatures and later stages of magma differentiation before crystallization. Compositionally these volatile granites are usually peraluminous, mica and alkali feldspar rich, varying in composition from leucocratic granite (alaskite) to quartz syenite and quartz monzonites. They form in continental settings. The suite includes some peralkaline varieties that may carry sodic amphiboles and form in continental but extensional environments. The volatile granites are associated with mineralisation that may include tin, tungsten, molybdenum, uranium, thorium, niobium, tantalum, and yttrium and rare earth elements. They are sometimes distinguished as fluorine-rich topaz (specialty) granites or as tourmaline granites. Pegmatite-forming melts with the potential for crystallizing gem minerals originate mostly during the crystallization of a parental granitic melt. Because the granitic melt initially crystallizes mainly feldspars and quartz, the residual melt is progressively enriched in elements excluded from the structure of these early crystallizing phases. Water and fluxing components such as B, P, Li, and F also increase in the late-stage granitic melt. The volatile components and other fluxes lower the viscosity and the solidification temperature, inhibit crystal nucleation, and greatly enhance chemical diffusion within the melt. If the concentration of volatiles, mainly H_2O, of the remaining residual melt exceeds its solubility limit, an aqueous fluid exsolves from the melt and promotes the formation of a miarole, or primary pocket. Nearly pure, gem-quality crystals of Be -, Li-, B-, and F-silicate minerals (along with other non-gem minerals) form in these pockets as the final products of crystallization (Simmons et al., 2003; London and Morgan, 2012).
Beryl is relatively rare because there is very little Be (2.1ppm) and Chromium and V are more common (92 and 97 ppm respectively) in the upper continental crust (Rudnick and Gao, 2003). Beryllium tends to be concentrated in rocks of the continental crust such as granites, pegmatite, black shale and their metamorphic equivalents. Cr and V are concentrated in dunites, peridotites, basalts of the oceanic crust and upper mantle and their metamorphic equivalents. However, high concentrations can also occur in sedimentary rocks, particularly black shale (Schwarz et al., 2002). Beryl can exist as yellowish green (heliodor), green (emerald), light blue (aquamarine), pink (morganite) and red (bixbite) based on the elements substituting principal constituent elements in its crystal structure ($Be3^{2+}Al2^{3+}Si6^{4+}O18^{2-}$). Emeralds are the green or bluish green, natural or synthetic gem variety of beryl which reveal distinct Cr and/or

V absorption bands in the red and blue-violet ranges of their absorption spectra and one of the most valuable gemstones after diamond and ruby. The color of emerald is due to trace amounts of Cr and/or V replacing Al in the crystal structure. The presence of Cr and V in the emerald structure causes a red fluorescence that enhances the luminosity of the blue green color, but if Fe^{3+} is present in the emerald crystal, this effect is suppressed (L.A. Groat et al., 2008). Formation of emerald requires unusual geologic and geochemical conditions for Be and Cr or V to meet. Emeralds, though exceedingly rare, can obviously form in a wider variety of geological environments than previously thought.

The classical model for emerald mineralization is formation of emerald at the contact of intruding pegmatites and intruded mafic-ultramafic rocks.

This model has been interpreted as the result of interactions between intruding granitic pegmatites and/or their accompanying fluids and pre-existing mafic or ultramafic rocks (Lams et al.,1996), or the invasion of fluids related to fertile granite or pegmatite, producing metasomatism in ultramafic/mafic rocks (Barton and Young, 2002). The emeralds then formed as a type of contact metamorphism or metasomatism at the borders of pegmatites or hydrothermal quartz ± feldspar ± mica veins and the surrounding metasomatized mafic or ultramafic rocks. The fluids would provide the beryllium necessary to form beryl, while the ultramafic or mafic rocks supplied the chromium and/vanadium necessary for the green color of the emeralds.

Contrary to this opinions, (Grundmann and Morteani, 1987; 1989; Nwe and Grundmann, 1990) state that schist hosted emerald deposits can also be formed due to tectonic activities that will cause syn-post tectonic growth of beryl in metasomatic zones- “blackwall zones” (e.g. Habachtal, Austria and Leydsdorp, South Africa deposits) during regional metamorphism. In these zones reactions either occur at the contact of pre-existing beryl and phenakite-bearing pegmatites (Leydsdorp), or else biotite, chlorite, or talc replace Be-rich Al-silicates such as muscovite in metasedimentary schist next to serpentinite. These reactions cause a release of the excess Be in muscovite to form beryllium-bearing phases (Habachtal). The original Be enrichment in muscovite schist is ascribed to submarine volcanic exhalation.

(Zwaan and Touret, 2000) have confirmed the syntectonic growth of emerald during regional metamorphism at Sandawana, Zimbabwe, thus advocating a multi-stage process leading to emerald growth in strongly deformed and metasomatized pegmatite/greenschist contact zones, as opposed to single-stage contact metamorphism at the border of intrusive pegmatite and ultramafic rocks.

In addition, researchers are recognizing that regional metamorphism and tectonometamorphic processes such as shear zone formation may play a significant role in certain emerald deposits (Grundmann and Morteani, 1989; Nwe and Grundmann, 1990; Vapnik et al., 2005; 2006).

These examples show that the schist-hosted emerald deposits are not genetically uniform and each deposit should be considered on an individual basis. The major emerald producing countries are Colombia (supplies an estimated 60%, worth more than $500,000,000 per year), Zambia (30%) and Brazil (10%) of the world's emeralds (Groat et al., 2008). Emeralds have also been mined in Afghanistan, Australia, Austria, Bulgaria, China, India, Madagascar, Namibia, Nigeria, Pakistan, South Africa, Spain, Tanzania, the United States, and Zimbabwe.

Emeralds occur in extensional carbonate-silicate-pyrite veins, pockets and breccias in an Early Cretaceous black shale-limestone succession in the Colombian deposits (Beus, 1979; Branquet et al., 1999a, 1999b; Cheilletz et al., 1994; Cheilletz and Giuliani, 1996; Giuliani et al., 1995; Giuliani et al., 1999; Giuliani et al., 2000; Govorov and Stunzhas, 1963; Hochleitner, 2002; Nassau, 1983; Ottaway et al., 1994; Renders and Anderson, 1986; Sunagawa, 2005). The geochemical model is essentially the same for Colombian emerald districts although they differ in age and tectonic setting. The eastern side of the Cordillera Oriental emerald deposits formed at the time of the Cretaceous-Tertiary boundary during a thin-skinned extensional tectonic event controlled by evaporite dissolution driven by gravity but, the western side of the Cordillera Oriental emerald deposits formed at the time of Eocene-Oligocene boundary linked to tear faults and associated thrusts developed during a compressive tectonic phase occurred prior to the major uplift of the Cordillera during the middle Miocene. The Colombian emerald mineralization is structurally related to tectonic blocks, 200 to 300m wide and emerald mineralization is contained in black shales altered by Na and Ca metasomatism. The deposits are unusual because there is no evidence for magmatic activity. Instead, the emeralds formed as a result of hydrothermal growth associated with tectonic activity. The highly alkaline (up to 40wt.% NaCl), parental hydrothermal fluids are thought to have evaporitic origin formed at depth from meteoric and formational water interacting with salt beds and evaporitic sequences interbedded with the black shales in the back-arc basins, where they were buried to depths of at least 7km and reached temperatures of at least 250 °C, migrated upwards through the sedimentary sequence along thrust planes and then interacted with the black shales. During this migration, major elements (Si, Al, K, Ti, Mg, and P) in addition to trace elements (Be, Cr, V, C, B, and U) and REEs were leached from the enclosing black shale via Na and Ca metasomatism and this was accompanied by development of a vein system filled by fibrous calcite, bitumen, and pyrite. The development of vein system again accompanied by initiation of extensional vein sets and hydraulic breccia development filled by muscovite, albite, rhombohedral calcite and dolomite, pyrite, bitumen, and by the precipitation in drusy cavities of fluorite, apatite, parisite [$Ca(Ce, La)_2(CO_3)_3F_2$], dolomite, emerald, and quartz. The role of organic matter in Colombian emerald mineralization has got two views: (1) hydrothermal brines transported evaporitic sulfate to structurally favourable sites, where it was thermochemically reduced by bitumen-derived H_2S to produce native sulphur and pyrite. The sulphur generated by this process reacted with organic matter in the shales to release trapped Cr, V, and Be, which in turn enabled emerald formation. (2) a redox reaction involving large organic molecules, a carbonic hydrate, and $SO4^{2-}$, that would generate large quantities of HCO^{3-} and H_2S, which then reacted with Ca^{2+} and Fe^{2+} (extracted from the black shale by the hydrothermal fluid) to produce calcite and pyrite, which are closely associated with the emeralds in the veins and breccias. The beryllium (3 ppm) in black shales in the area of the emerald deposits was transported, as hydroxide complexes in acid solution, or as carbonate-hydroxy-halide-beryllates in near-neutral to alkaline solutions, only a short distance to be re-precipitated (in part) in the form of emerald. A local origin is supported by the distinct stratigraphic control of the emerald-bearing veins. Trapiche emeralds occur in black shales or albitized black shales near emerald-bearing veins for example consist of a hexagonal prismatic core overgrown with an outer shell of emerald with six planar arms radiating from the edges of the core. The arms contain inclusions of albite and carbonate but can also contain lesser amounts of bitumen, pyrite, monazite, K-feldspar, epidote, zircon, and apatite. This phenomena is explained in both beryl and corundum to skeletal (or dendritic) growth, in which the edges and corners of the crystal grow much faster than the faces The distribution of Be in the different phases of the hydrothermally altered black shale hosting the emerald deposits indicates that Be mobility is associated with the breakdown of Fe–Mn oxyhydroxide phases. The amount of Be that can be mobilized (0.7 ppm) may represent up to 18 wt. % of the total Be contained in the black shale. The current model bears resemblance to that of sediment-hosted stratabound and strataform base metal deposits. The brine fluids responsible for emerald formation are remarkably similar to oil-field brines and brines involved in the formation of Mississippi Valley-type Pb–Zn deposits. Emeralds from Colombia in general have a more intense colour than Fe-bearing emeralds from pegmatitic ultramafic environments because $Fe3^{+}$ quenches the red fluorescence. The removal of Fe from the system as pyrite is an important factor in the development of the spectacular colour of Colombian emeralds.

The Zambian emerald mines are located in the Kafubu area, about 45 km SW of Kitwe in the central part of the country. The geology and geochemistry of Zambian Kafubu area emerald has been studied by (Hickman, 1973; Cahen and Snelling, 1966; Cahen et al., 1970a; 1970b; Daly and Unrug, 1983; Sliwa and Nguluwe, 1984; John et al., 2004; Zwaan et al., 2005; Milisenda et al., 1999 as sited in Antonín, 2004). The oldest metamorphic rocks of the Kafubu area, comprising mainly quartz-feldspathic gneiss and granite gneiss, are exposed in structural elevations of basement domes. These Paleoproterozoic rocks underwent polyphase deformation and high-grade metamorphism of Ubendian age (ca. 2000–1800 Ma). The Kafue anticlinorium and its marginal basement domes are rimmed by extensive outcrops of younger meta-sediments. The Muva supergroup (Mesoproterozoic) overlays basement rocks with a distinct angular unconformity, marked by a regional ridge of basal quartzites. These two units were jointly folded, which resulted in the sub-parallel trend of lithological boundaries. The Muva Supergroup comprises medium to coarse-grained sugary and friable metaquartzites showing banding of probable tectonic origin, fine-grained quartz-mica schists, and talc-chlorite-actinolite ± magnetite schists. Magnesian metabasic schists that host emerald mineralization have been interpreted as being derived from ultrabasic rocks. The emerald deposits are hosted by Cr-rich (3000 to 4000 ppm) talc-chlorite ± actinolite ± magnetite metabasites of the Muva Supergroup, which have been identified as metamorphosed komatiites. The metabasite horizons are overlapped by a major field of Be bearing pegmatites and hydrothermal veins ~10km in length that was emplaced during the late stages of the Pan African Orogeny (~530 Ma). Economic emerald concentrations are almost entirely restricted to phlogopite reaction zones (typically 0.5 to 3m wide) between quartz-tourmaline veins and the metabasites. Possible role of an evaporitic environment, mainly with reference to stratiform and finely banded quartz-tourmaline rocks with phlogopite rocks carrying beryl mineralization represent metamorphosed salt clays for Kafubu emerald is also suggested. Chemical analyses indicate that the formation of phlogopite schists from the metabasite involved the introduction of K_2O (8 to 10 wt. %), F (2.7 to 4.7 wt. %), Li_2O (0.1 to 0.7 wt. %), Rb (1700 to 3000 ppm), Be (up to 1600 ppm), Nb (10 to 56 ppm), and significant amounts of B.

In Brazil the main emerald deposits are located in the states of Bahia, Minas, and Goiás and the country became a significant emerald producer exporting $50 million annually in emeralds during the 1980s (Giuliani et al., 1990; Giuliani et al.,1997). Brazilian emerald deposits are classified in to two classes: (1) deposits with emerald grades between 12 and 165 g/t are those in which pegmatites intrude the mafic and ultramafic rocks. The pegmatites have been desilicified and altered to plagioclasites. The mafic and ultramafic rocks were (K, Na) metasomatized to emerald bearing mica schists (phlogopitites) by hydrothermal fluids channelled by the pegmatites. The Be is almost certainly magmatic in origin. Emerald-bearing quartz veins are also found in several of the deposits (2) deposit with emerald grades varying between 50 and 800 g/t, is associated with ductile shear zones cutting mafic and ultramafic rock formations. The emeralds occur in phlogopitites and phlogopitized talc-carbonate schists. The talc schists provided sites for thrusting that gave rise to the formation of sheath folds. Emeralds are most commonly found in the cores of the sheath folds and along the foliations. Both are in Proterozoic volcano-sedimentary rocks with intercalations of mafic and ultramafic rocks. Isotopic data ($\delta^{18}O$ and δ D for emerald and coeval phlogopite) are consistent with both magmatic and metamorphic fluids. However, the absence of granites and related pegmatites, and the low Be concentration in the volcano-sedimentary sequence (<2 ppm), exclude a magmatic origin for Be. A metamorphic origin is therefore proposed for the second type deposits parental fluids.

Emerald mineralization at Kilkile area of Ethiopia has not been yet studied, the data available are limited to draft reports, which do not present genetic classes. In the current study; mineralogical, structural, petrological and geochemical aspects of the host and country rocks, associated gangue minerals and emerald has been studied to propose the genetic model. Mining at Kilkile area is limited to traditional way with few semi-mechanized mining methods. Pits established without design and organization. This caused irregular supply and finest lose. In the current study; geotechnical measurements are also included to suggest some methods for mining and processing.

CHAPTER TWO

2 REGIONAL GEOLOGY

2.1 Regional geologic setting

2.1.1 Pan African Orogeny

Tectonic, magmatic and metamorphic activities for crust that was once part of Gondwana during Neoproterozoic to earliest Paleozoic age are described as Pan-African event. Juvenile (mantle derived) Neoproterozoic supra-crustal and magmatic assemblages (Arabian-Nubian Shield, Damara-Kaoko-Gariep Belt, Lufilian arc of south-central and south-western Africa, west Congo belt of Angola and Congo Republic, trans-Sahara belt of west Africa, Rokelide and Mauretania belts along the western Part of the west African craton) and poly-deformed high-grade metamorphic assemblages (Mozambique Belt of east Africa, Zambezi belt of northern Zimbabwe and Zambia, migmatitic terrains of Chad and Central African Republic, Tibesti massif in Libya and the western parts of Sudan and Egypt) are the two broad orogenic or mobile belts within the Pan-African event (Kroner and Stern, 2005). East and West Gondwana are sutured along the length of East African Orogeny due to arc accretion collage and micro-continental terrains collapse driven by Neoproterozoic closure of the Mozambique Ocean (Timothy et al., 2003).

2.1.2 Geodynamic evolution of East African Orogeny (EAO)

The Late Proterozoic rocks of NE Africa (Saudi Arabia, eastern Egypt and eastern Sudan) record a succession of mild collisions resulting from the successive accretion of island arcs (Shackleton, 1986). Gondwanaland was assembled during the Neoproterozoic from two fragments- East and West Gondwanaland along the Pan-African Mozambique Belt of East Africa. This suggestion is supported by the lithological association characteristic of the Mozambique Belt and its extension to the north, the Arabian-Nubian Shield (ANS). The basement in northeast Africa and Arabia is referred to as Arabian Nubian Shield predominantly juvenile continental crust formed by differentiation of mantle melts largely without reworking of preexisting continental crust (Stern, 1994). The ANS represents the northern part of EAO which formed by collision between East and West Gondwana at the end of a Wilson cycle. Geochemical and isotopic signatures indicate that these rocks are dominantly mantle-derived juvenile crust (Stern, 1994; 2002). The shield is dominated by supra-crustal meta-volcanic including volcano-clastic and immature sediments mostly metamorphosed in the green schist facies, variously deformed and intruded by granites, gabbros and dikes. It extends from Jordan and Israel in the north, through to Ethiopia and Sudan in the south (Berhe, 1990; Kroner et al., 1991; Stern, 1994; Teklay et al., 1998; 2001). In Ethiopia, the ANS merges with the Mozambique Belt which is the southern half of the EAO and which accommodated the most intense collision between East and West Gondwana fragments.

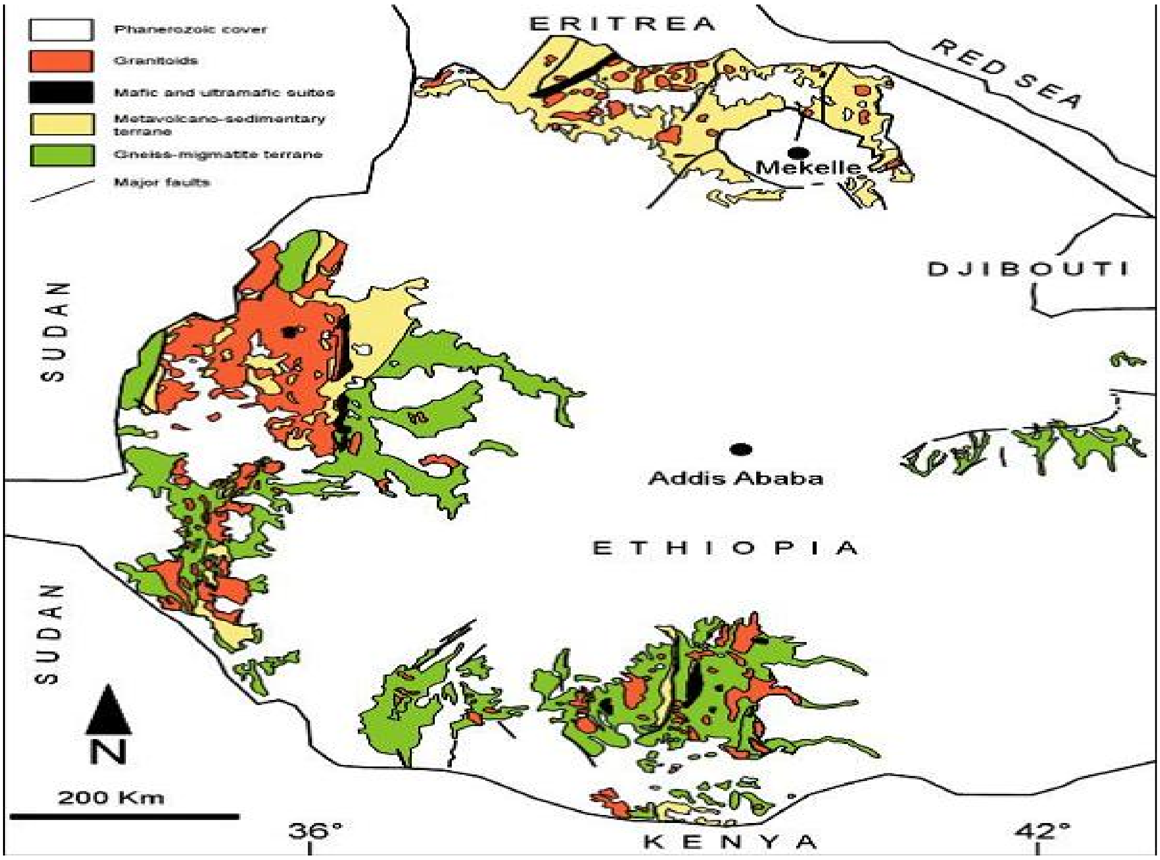


Figure 2.1 Distribution of the low grade volcano-sedimentary sequences of the ANS and high grade gneisses and migmatites of the Mozambique Belt in Ethiopia, adopted from (Asrat et al., 2001)

2.1.3 The Precambrian of Southern Ethiopia

The Precambrian of southern Ethiopia occupies an important position within the Pan-African Mozambique Belt and the Arabian-Nubian Shield, which together, form the East African Orogeny. Two distinct tectono-stratigraphic terrains: - (1) granite-gneiss terrain and (2) ophiolitic fold and thrust belts are present in the Precambrian of Southern Ethiopia (Yibas et al., 2002). Granite-gneisses consists of para-ortho-quartzofeldspathic gneisses and granitoids (rocks vary from granitic gneisses to undeformed granites and range compositionally from diorites to granites) intercalated with amphibolites and sillimanite–kyanite-bearing schists. The granitoid gneisses form an integral part of the granite-gneiss terrain, but are rare in the ophiolitic fold and thrust belts (rocks composed of mafic, ultramafic and meta-sedimentary rocks in various proportions).

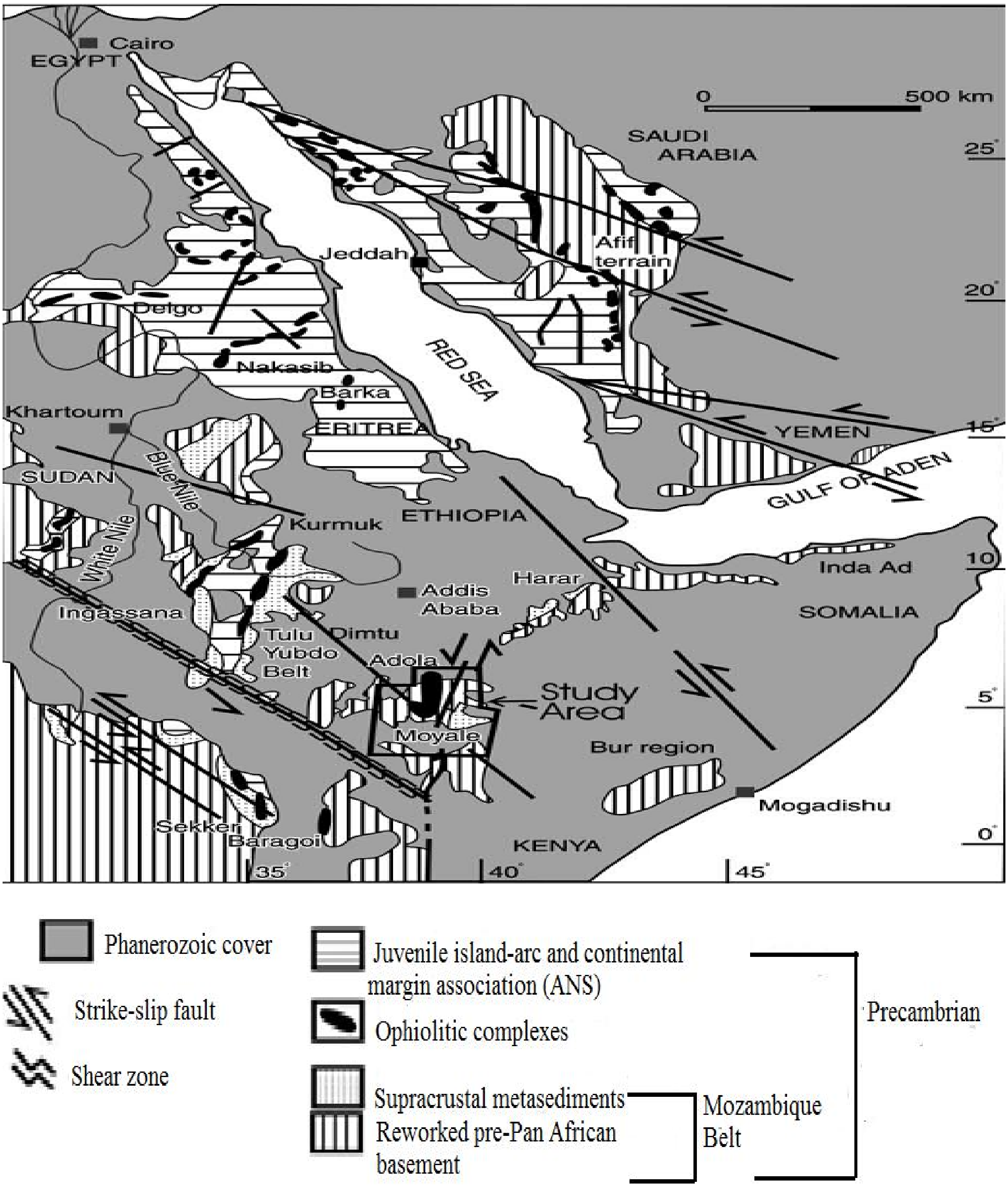


Figure 2.2 Geological map of northeastern Africa, (modified after Shackleton, 1997), showing the Precambrian of southern Ethiopia within the confines of the East African Orogeny

2.2 Emerald Mineralization and Geological Settings

A number of genetic classification schemes, using various techniques including (refractometry, specific gravity determinations, luminescence, visible and infrared spectrometry, solid and fluid inclusion studies and trace element geochemistry), have been proposed for emerald deposit other than the classic model, “Be-bearing pegmatites interact with Cr bearing ultramafic or mafic rocks” for emerald to form. Dereppe et al. (2000) used Artificial Neural Networks (ANN) based on 450 electron microprobe analyses to classify emerald deposits. This classification considered the relation of emerald formation with the host rock, hydrothermal activities, metamorphism and tectonism. Accordingly five classification schemes have been proposed- deposits those related to: (1) granitic pegmatitic intrusions and hydrothermal veins in mafic-ultramafic rock; (2) tectonism in mafic-ultramafic rocks; (3) oceanic suture zones; (4) thrusts and faults in sedimentary black shale rocks; and (5) a granite-cupola. Schwarz and Giuliani (2001) and Schwarz et al. (2001) as sited in Groat et al. (2008) recognized two main types of emerald deposits based on intrusives and tectonic structures- deposits those related to: (1) granitic intrusions and (2) tectonic structures, such as thrust faults and shear zones. Granitic intrusion related deposits are further classified based on the presence or absence of schist at the contact. Tectonic structures controlled deposits are subdivided into schists without pegmatites and black shale with veins and breccia. However, researchers pointed out that location within major suture or shear zones does not necessarily rule out a connection with granitic intrusions or mineralization related to granitic intrusions may also be influenced by tectonism (Zwaan, 2006; Abdalla and Mohamed, 1999). The typical evidences for this are the Egyptian deposits that has been classified as schists without pegmatites, but the mineralization is closely related to that of pegmatite veins, Swat Valley deposits in Pakistan which shows a potential link between emerald formation and fluids of pegmatitic origin and Leydsdorp in South Africa in which emeralds grew syntectonically, but are closely related to pegmatites. Further classifications also made on the basis of: igneous connection (those with a direct igneous connection and where such a connection is indirect or absent (i.e., metasomatic), associated magma and/or the host rock and origin. The Nigerian deposits are considered to be unusual because they are associated with metaluminous (rather than peraluminous) granitoids (Barton and Young, 2002). The Swat Valley deposits are classed as carbonate hosted, but the source of the Cr is the associated ophiolitic melange. For this reason the Swat Valley deposits could be classified as mafic/ultramafic. More recently, based on geological (the timing of pegmatite intrusion and emerald formation; the presence of pegmatites and evolved granites; the lack of biotite and mafic or ultramafic rocks) and chemical (oxygen isotope composition and lithium content of the micas) criteria, (Sabot, 2002 as sited in Groat et al., 2008) proposed six classes of emerald deposits:

"(1) those associated with miarolitic cavities in granites or pegmatites without metasomatic alteration zones (e.g., Kaduna, Nigeria and Emmaville, Australia); (2) deposits in which pegmatites and emeralds are contemporaneous and the latter occur in metasomatic alteration zones in mafic and ultramafic rocks with presence of tourmaline and the lithium content of biotite in the alteration zones exceeds 1000 ppm (e.g., Carnaiba, Brazil, and Kamaganga, Zambia); (3) deposits in which pegmatites and emeralds are contemporaneous and the latter occur in metasomatic alteration zones in mafic and ultramafic rocks with absence of tourmaline and the lithium content of biotite in the alteration zones is between 100 and 1000 ppm (e.g., Mananjary, Madgascar); (4) no pegmatites contemporaneous with emerald formation but metasomatic alteration zones are present (e.g., Ianapera in Madagascar, the Urals in Russia, and Poona in Australia); (5) no pegmatites and the emeralds occur in carbonate rocks without albite and pyrite (e.g., Swat, Pakistan); and (6) no pegmatites and the emeralds occur in rocks composed of albite and pyrite with evidence of evaporite dissolution (e.g., Colombia)." Therefore; geological settings for emerald mineralization is variable, occur in different settings as far as sources for Be, Cr and/ V are available.

CHAPTER THREE

3 LOCAL GEOLOGY

3.1 Lithology

The field mapping was conducted at Kilkile local area; from April 14-21, 2019. During the course of field mapping about eight mining and exploration pits have been visited. Hallo, Hoji Duroma, Milki Boru and Waritu kufa pits are mining pits developed to semi-mechanized mining in the area. The reaming four (Oda Eba, Kubi kufa, Bu'a Obsa and Haro Kufa) pits are exploration pits opened by local miners. The geology of Kilkile area comprises meta-basic assemblages (Serpentinite, tremolite-talc schist, chlorite schist, chlorite-talc schist, epidote-quartz-hornblende schist and biotite-amphibolite schist), alteration (metasomatised) biotite schist, pegmatite dykes/veins and quartz-apatite-beryl veins/vein-lets (Figure 3.7).

3.1.1 Meta-basic assemblages

In a symmetrically exposed units in the mining pits at the study area, meta-basic rocks occupy the position adjacent to metasomatized biotite schist. Emerald mineralization at the area is confined to the contacts of altered (metasomatized) meta-basic rocks and pegmatite dykes/veins. Therefore, since the existence of these rocks is essential for emerald mineralization, it is usual to access these rocks in almost all mining pits. Eastward or westward traverses in the either side of the vertical too sub-vertical pegmatite dykes lead to identical successive rock units, implying that the pegmatite dykes are concordant to meta-basic assemblages. The pegmatite or quartz veins/vein-lets sometimes display discordance to the units for the reason that they are shouted from major dykes following weakness zones. As far as meta-basic assemblages are concerned, they are composed of a collage of rock units depicting certain mineralogical variations. The major rock units that constituted the meta-basic assemblages are: - Serpentinite, tremolite-talc schist, chlorite schist, chlorite-talc schist, epidote-quartz-hornblende schist and biotite-amphibolite schist.

3.1.1.1 Serpentinite

The Serpentinite unit which forms a hill in the study area gradually changes from Serpentinite core to tremolite, chlorite and finally to talc at the margin. The rock unit is greyish green, fine to medium grained and weakly foliated. It is composed of Serpentinite, talc, tremolite, chlorite and subordinate amount of chromite. Chromite, which occurs as rectangular crystals, is found as disseminations and veinlet in Serpentinite. The Serpentinite developed Boxwork structures formed due to iron and silica rich veinlet.

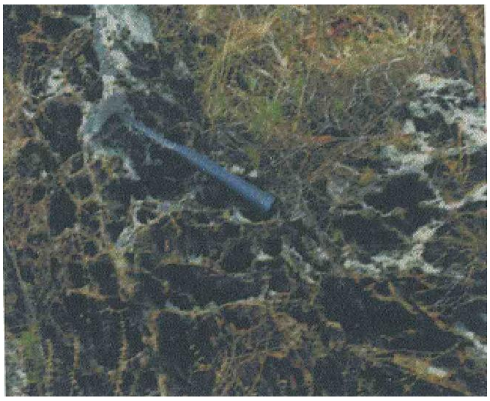


Figure 3.1 Boxwork structure developed on the Serpentinite unit, photo taken facing south

3.1.1.2 Tremolite-talc schist

Tremolite-talc schist is exposed in stream sections and gullies as discontinuous patches covering wider area. It is greenish gray, fine to course grained, schistose and composed of flaky talc (80%), xenoblastic tremolite (15%) and xenoblastic (iron oxide, 5%). Talc and tremolite show a well-developed parallel alignment. It has sharp to gradational contact with Serpentinite and boudinaged quartz vein is developed at the contact zone. This unit is moderately-strongly foliated with foliation trending N-S and occasionally, it hosts chlorite-talc and chlorite schist with/without epidote-quartz-hornblende schist.

Figure 3.2 Tremolite-talc schist in Waritu Kufa mine, photo taken facing south

3.1.1.3 Chlorite schist

This zone has a maximum thickness of about 10cm, greyish and fine to course grained, schistose and composed of flaky chlorite (85%), xenoblastic iron oxide (15%), flaky biotite (trace) and xenoblastic quartz (trace). Chlorite shows a well-developed parallel alignment. At places, it depicts crenulation cleavage, particularly where sheared. It is strongly foliated and occur as thin seams along with chlorite-talc schist adjacent to metasomatized zone.

3.1.1.4 Chlorite-talc schist

The zone is 10cm thick, brownish-greyish-greenish, fine to medium grained, schistose and it is composed of flaky talc (83%), flaky chlorite (15%) and xenoblastic opaque (iron oxide, 2%). Talc and chlorite show a strong well-developed parallel alignment. At places, it is cut by discordant quartz veins and vein-lets, limonitized and silicified. It is strongly foliated and at places, strongly sheared, where shearing is manifested by boudinaged and folded quartz veins and vein-lets. The brownish tint on it is due to limonitization of iron oxide. It is intercalated with chlorite schist and both occur as thin seams next to metasomatized zone and grades in to thick, irregular and competent hornblende dominated schist unit.

3.1.1.5 Epidote-quartz-hornblende schist

This unit is dark greyish, fine to medium grained, schistose and composed of xenoblastic hornblende (40%), xenoblastic quartz (20%) xenoblastic plagioclase (15%), xenoblastic epidote (20%), xenoblastic sphene (5%) and xenoblastic iron oxide (trace). Hornblende, quartz, epidote and sphene show a well-developed parallel alignment. At places, quartz veins display folding (shortening) and boudinage (lengthening) due to shearing. The unit is slightly-moderately foliated, irregular, about 5m thick and more competent unit.

3.1.1.6 Biotite-amphibolite schist

These rocks probably comprise more than 70 % of the total volume of meta-basic rocks in the mapping area. They are fine-grained, weakly to well-foliated rocks composed predominantly of green amphibole, intermediate plagioclase, quartz and biotite. A laminar, streaky texture is observed on biotite-amphibolite schist.

3.1.2 Biotite schist

Biotite schist unit is the unit immediately adjacent to the pegmatite dykes/veins, typically formed as reaction zones along the contacts of quartz-plagioclase-muscovite pegmatite dykes/veins and meta-basic rocks. These zones are 20-30cm wide. The simplest type of these rocks is dominated by flaky biotite (90%), xenoblastic quartz (5%) and xenoblastic opaque (5%). Accessory subhedral to euhedral porphyroblastic aggregates of beryl and apatite are also available as an inclusion. They are dark gray, fine-course grained, schistose with perfect grain-shape orientation of the biotite crystals. Biotite and quartz show a strong well-developed parallel alignment.

Figure 3.3 Biotite schist (a narrow zone between red lines, indicated by a green arrow) in Hoji Duroma mine, photo taken facing south

Generally, pegmatite and quartz veins locally and preferentially intrude meta-basic assemblages with a manifestations of boudinaged, pinched and swelled structures of lenticular glassy quartz lumps and feldspar/quartz dominated pegmatite.

3.1.3 Pegmatite dykes/veins

During the fieldwork, pegmatite dykes/veins of variable thickness were encountered in different mining and exploration pits. The general strike of the Pegmatite dykes/veins is N-S with a few exceptional striking NE-SW/NW-SE. All pegmatite dykes are course grained, pinkish coloured in most and greyish coloured in few pits. They range in thickness from less than a meter to about five meters. The pegmatites are composed of dominantly plagioclase, quartz and muscovite with trace biotite and minor beryl and apatite crystals. The main body shows xenoblastic granular texture. Concentrated aggregates and crystals of muscovite, apatite and quartz occur locally. Quartz, apatite and beryl inclusions commonly developed in wall rocks immediately adjacent to pegmatites. The fabric of the pegmatite body is complex with varying intergrowth fabrics, local mineral aggregates, irregular quartz veins and cores. The minor alignment of constituting minerals at the margin of pegmatites and close vicinity to the meta-basics rocks might suggest minerals growth normal to cooling margins. The weak zonation of the pegmatite body is evident from same principal minerals seen in various parts of the main body but in different proportions. The proportions of quartz, plagioclase and muscovite shows a significant variation from the inner to the outer body of the pegmatite dykes.

Quartz ranges from 100% -10%, plagioclase ranges from 69% - 0%, muscovite ranges from 69% - 0% and opaque minerals and biotite ranges from 3% - 0%. The core composed of 100% - 94% quartz, 3% opaque minerals, 2% plagioclase and 1% muscovite and accessory aquamarine and apatite crystals. Grain size varies in a remarkable manner. Muscovite sheets up to 10cm across, 60cm smoky quartz crystal, about 5cm plagioclase crystals and 1cm blue aquamarine crystal are seen in pegmatite body at Milki Boru mining pit. Tourmaline occurs as needle like, scrambled rosettes with hair line cracks. The opaque minerals near quartz core of the pegmatite dykes are Nb-Ta minerals. Biotite Patches are found in the marginal zones of the pegmatite dykes. The pinkish coloured pegmatite dykes usually occur as huge blocks or discontinuous patches whereas, the greyish coloured ones occur as continuous huge blocks. Compositionally, the pinkish pegmatite dykes are dominated by quartz, plagioclase and subordinate biotite (3%), whereas the greyish pegmatites are dominated by muscovite, plagioclase and quartz respectively. At the contact with the surrounding meta-basic rocks there is a metasomatized external border zone up to 30cm wide. Dykes may be several metres long, emanating from major granitic pegmatite intrusion. Except at the contact with meta-basic rocks where muscovite, plagioclase and quartz mineral grains display a certain range of deformation (a schistose structure), the pegmatite dykes are un-deformed. Small folds immediately adjacent to dykes appear to be related to intrusion and plastic deformation of wall-rocks. The emplacement and shape of these vertical to sub-vertical, un-deformed and fracture-filling pegmatites was therefore controlled by fractures that post-dated the regional metamorphism of the country rocks.

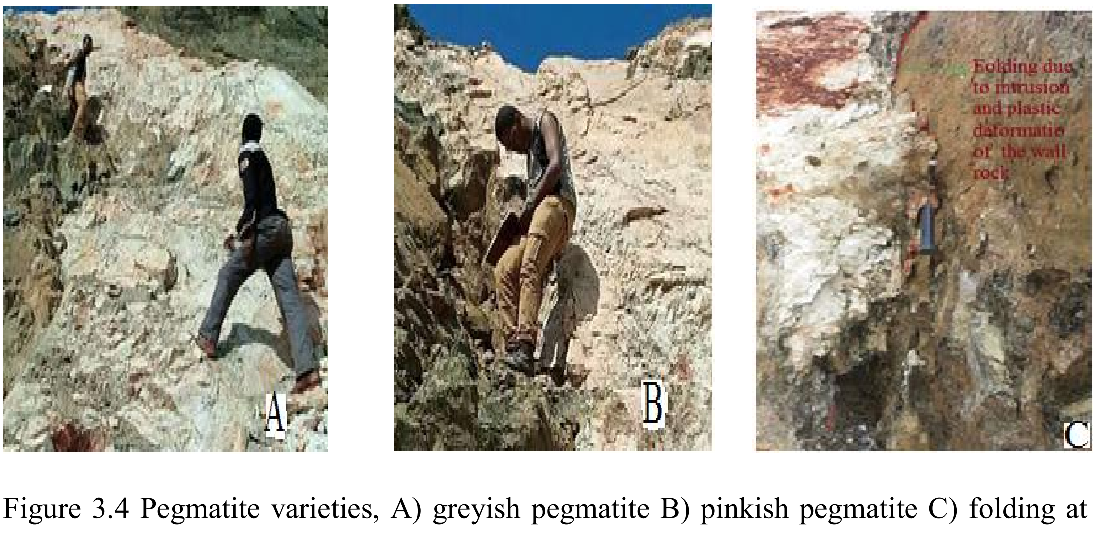


Figure 3.4 Pegmatite varieties, A) greyish pegmatite B) pinkish pegmatite C) folding at the contact with meta-basic rocks, photos taken facing south

3.1.4 Quartz-apatite-beryl veins/vein-lets

Openly folded and boudinaged quartz veins/vein-lets bordered by thin boudinaged, pinched and swelled pegmatite veins might possibly squeeze minor faults near the contact or fill the shear initiated extensional fractures in the meta-basic assemblages. The veins incorporated white-milky-glassy crystalline quartz, hexagonal yellow green beryl (heliodor) and prismatic green apatite. Sometimes concentrate tourmaline crystals may appear locally with disseminated apatite lenses. The crystal enveloped face may represent wall of an original extensional shear driven fractures. Greenish beryl (emerald) crystals with hairline fractures and a strip of opaque and translucent bands alternating parallel to the crystal axis occur occasionally. Light greenish to bluish beryl (aquamarine) crystals are rarely scattered within a margin of coarser pegmatite veins bordering quartz-apatite-beryl veins/vein-lets.

3.2 Structures

The phases of deformation at Kilkile area produced linear (lineations, joints), planar (foliations, schistosities), folds and shear structures.

3.2.1 Lineations and joints

The lineations in the rocks are expressed by N-S trending quart and plagioclase porphyroblasts. Particularly, on epidote-quartz-hornblende schist the intersections of axial planes of shear and crenulation cleavage produced N-S trending lineations. Brittle-ductile shear deformation resulted a weakness zone filled by pegmatite dykes/veins. The shape of the un-deformed dykes/veins attain the shape of the weakness zones and displayed as boudins and folds. Shearing also resulted E-W trending extensional joints filled by quartz and secondary fibrous minerals like talc. The other sets of joints are lithological disconformity joints between different lithological units trending N-S.

3.2.2 Foliations

The regional foliations expressed by flaky micas and talc or quartz grains generally trends N-S with few exceptions to east or west and dips east or southeast at different angles. The bands of micas parallel to the foliation planes gives rise to the schistose foliation on different lithological units. This regional foliation overlaps with axial planes of the micro-folds and shears.

3.2.3 Folds

The tight micro-folds in the area are resulted from folding of S_1 foliations and have N-S trending axial plane. These micro-folds have an inter-limp angle of about 15^0-20^0 with limps dipping either southeast or southwest. The brittle nature of shearing boudinaged these micro-folds (Figure 3.5 B and C).

3.2.4 Shears

The brittle ductile nature of shearing in the area is expressed by fragments of fracture filling quartz veins/vein-lets. The fracture filling quartz veins/vein-lets show pinch, swell, fold and boudinage structures in the weakness zones resulted from brittle-ductile shearing. The thin quartz veins/vein-lets display tight folding at shortening and boudinage at lengthening sites resulted by shearing.

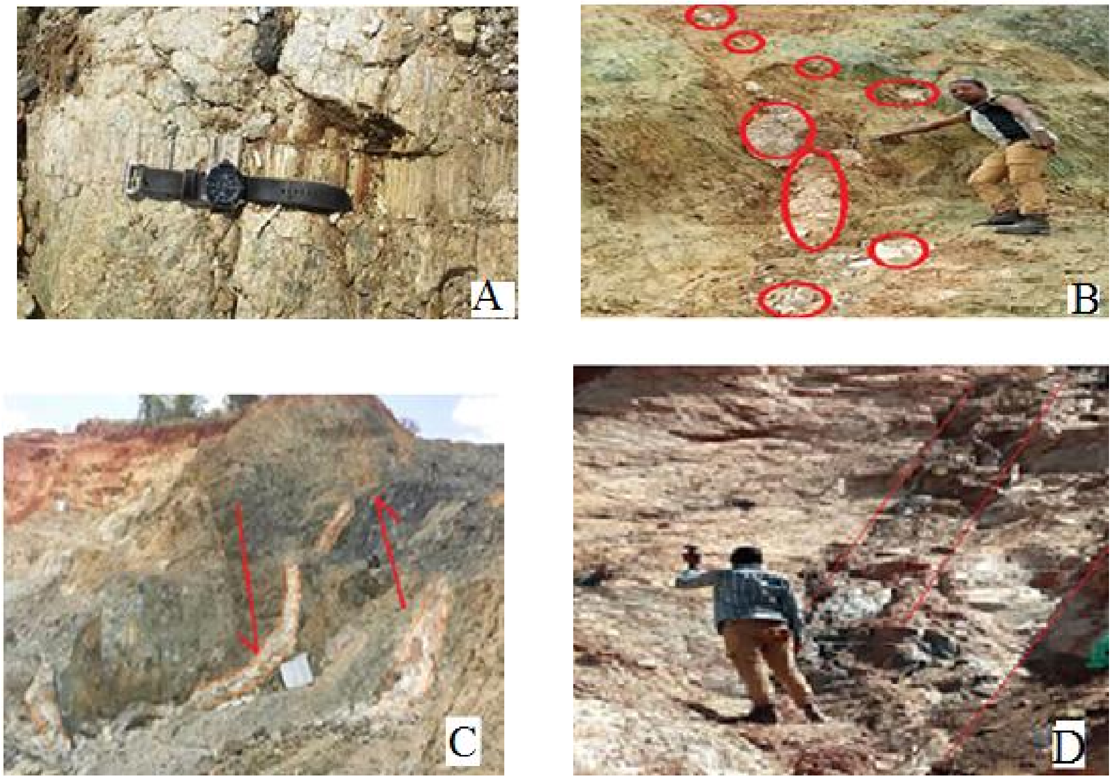


Figure 3.5 structural components A) secondary fibrous talc developed in E-W trending extensional fracture B) boudinaged, pinched and swelled pegmatite vein (hummer pointed is thin biotite schist where emerald is confined C) boudinaged, pinched and openly folded quartz vein D) lithological disconformity joints (red lines); photos taken facing south

3.3 Metamorphism and metasomatism

The metamorphic rocks of the area incorporates tremolite-talc schist, biotite-talc schist, epidote quartz-hornblende schist, chlorite schist and biotite schist. At Kilkile area, the rock forming mineral assemblages are biotite + talc + tremolite + epidote + quartz + hornblende + sphene + chlorite + magnetite (opaque). The epidote, hornblende and sphene assemblage indicates an epidote-amphibolite facies (greenschist facies) for metamorphosed mafic rocks whereas the talc, tremolite, chlorite and magnetite assemblage indicates greenschist facies for metamorphosed ultramafic rocks. Therefore, the rocks of Kilkile area can be considered as mafic-ultramafic rocks metamorphosed to epidote-amphiboloite facies-greenschist facies. The mineral assemblage suggests conditions of peak metamorphism of 350^{o}C to 550^{o}C at medium pressure. However, talc occurrence in the mineral assemblage might suggest higher temperature range of about 310^{o}C -700^{o}C for aqueous and carbon dioxide rich fluids respectively (Best, 2003). The abundance of biotite (80%) at the contact with the pegmatite body might be due to retrograde metamorphism of the meta-basic rocks resulting horblende replaced by biotite. Formation of thin chlorite schist at the interphase of biotite schist and epidote-quartz-hornblende schist might be due to metasomatic alteration of hornblende and biotite in to chlorite. Chloritization of biotite and hornblende at deformed zones and minor silicification at the contact with pematite veins are the alterations observed in the area.

3.4 Mineralization

The area is mineralized in beryl, tourmaline and apatite (Figure 3.6). Emerald frequently occurs at mica schist-pegmatite dyke contact and quartz-apatite veins and rarely in mica schist and pegmatite dykes. It occurs as aggregates of several crystals or a coherent euhedral or subhedral hexagonal prismatic crystal reaching up to 3cm in length. The emerald contains fine cracks, light-medium-deep green in colour, frequently includes biotite, apatite and quartz. Mostly, wall-rock hosted emeralds are light green, prismatic, developed with long axis of the crystal parallel/cross-cut to the regional foliation and inclusions of quartz and biotite grains aligned parallel to the longer axis of the crystal. Moreover, in wall-rock hosted emeralds, the interruption of crystal growth is frequently observed in the side of pegmatites at pegmatite mica schist contact. This might be due to the inability of brine fluids to conduct through and crystallize in the coherent quartz or syn-crystallization of quartz and emerald or replacement of one for the other. The field observation depicts the replacement of quartz by emerald since emerald has quartz inclusion in the crystal growth progress direction. In the veins, emeralds are subhedral, deep green with inclusion of dark opaque minerals and quartz dispersed in the crystal. In the veins, emeralds are confined at boudinaged and openly folded localities as these are sites for pregnant brine solutions to drop the crystalized phase. The pinched areas have finer deep green emeralds. In contrary to these, emeralds rarely formed within the mica schist are light green, prismatic, have more biotite inclusion and cross-cut the regional foliation. The pegmatite hosted emeralds are incoherent, light green, subhedral and invaded by dispersed solid inclusions of clay material (due to kaolinization of the host pegmatite vein). Elongated, incoherent, scrambled and needle like tourmaline crystals are confined in the quartz veins. These columnar structured tourmalines are localized within quartz veins and sometimes host emerald. The prismatic deep green apatite crystals are confined to the peripherals of the pegmatite dykes at the contact with mica schist. At these sites emerald is included with quartz grains derived from pegmatites, biotite from mica schist and apatite crystalized at the contact.

Figure 3.6 Emeralds formed at different sites A) exactly at the contact, crystal growth by replacing quartz B) at proximity to the contact, emerald crystal cross-cut the regional foliation (larger crystal) and the foliated mica grains curved around the crystal, exactly at the contact (top margin) it is parallel to the foliation C) at the interior of the mica schist, emerald crystal is light green and cross-cut the regional foliation D) emerald formed at the contact E) emerald formed in pegmatite F) emerald formed in vein G) needle shaped aggregates of prismatic tourmaline crystals

The contact zone mica schist has higher content of calcium and phosphorus oxides. This might be resulted from the composition of pegmatites. If the pegmatitic intrusions carry hot aqueous solution rich in phosphorus, boron and fluorine, it persists to later stage of magma differentiation before crystallization. As a consequence, these components prevent from crystalizing phase and enriched in the residual melt. Further propagation in to the country rock will result in a drop in viscosity, pressure and temperature. Finally, their precipitation is accompanied with formations of minerals like apatite at the contact or in the meta-basic rocks due to calcium derived from meta-basic rocks.

3.5 Pits distributions

The general N-S trending of the pegmatite dykes/veins and hydrothermal quartz-veins resulted in pits distribution along N-S direction since emerald is confined to the contacts of these dykes and veins with the meta-basic rocks. From the total of eight mining and exploration pits encountered in the mapping area, the absolute locations of the most pits manifest that the pits are aligned on a single dyke/vein. Hallo (HA) pit is located at 0503210E, 0598737N and Bu'a Obsa (BO) pit is located at 0503191E, 0598074N coordinates respectively. Ooda Eba (OE) pit is located at 0504068E, 0601492N and Waritu Kufa (WK) pit is located at 0504152E, 0601097N coordinates respectively. Hoji Kufa (HK) pit is located at 0504259E, 0601489N and Hoji Duroma (HD) pit is located at 0504240E, 0601301N coordinates respectively (Figure 3.7). Therefore, we can understand that these sets of pits, Hallo and Bu'a Obsa; Ooda Eba and Waritu Kufa; Hoji Kufa and Hoji Duroma pits are established on a single N-S trending dyke/vein since they found on nearly same longitude. The Milki Boru (MB) pit located at 0505072E, 0601404N coordinate has a pegmatite dyke orienting in a similar N-S direction. Furthermore, the average thickness of the pegmatite dykes/veins with N-S general orientation is 2-5m. The similarity in the orientation and thickness of the dykes/veins in these pits manifest that these pits are distributed on a major N-S orienting pegmatite dykes. On contrary, the Kubi Kufa (KK) pit located at 0503289E, 0598659N coordinate has pegmatite vein with orientation of NE-SW. The thickness of the vein in Kubi Kufa ranges from 20-60cm, thicker at its south-western side and gets thinner in north-easterly direction. From the existing three evidences: - proximity to the pegmatite dyke on which Hallo and Bu'a Obsa pits are found, its NE-SW orienting pegmatite vein and north-easterly decrease in the thickness of the vein in the Kubi Kufa pit; we can possibly conclude that the Kubi Kufa pit is located on a shoot dyke/vein branched from major dyke on which Hallo and Bu'a Obsa pits are found. The dykes/veins trending other than N-S direction might be those intruded into the NE-SW or NW-SE trending younger generations of fault systems or intruded into the E-W trending shear generated extensional fractures, whereas the N-S trending dykes/veins are those intruded into the N-S trending Kenticha deep seated fault systems. Since the productive pits at different locations are established along north-south direction at considerable distance and located on the same longitude, only differ in latitude, it is clear that the pegmatites in the area are extensive along their strike (N-S). Therefore, areas in between the productive pits are also expected to host emerald. However, it is difficult to estimate the number of dykes in the area, due to a very limited exposure of the area, with the exception of active mining and exploration pits, we can possibly estimate of the number of pegmatite dykes in the area on the order of hundreds with most dykes or veins trending N-S and few shoot dykes/veins trending in other directions.

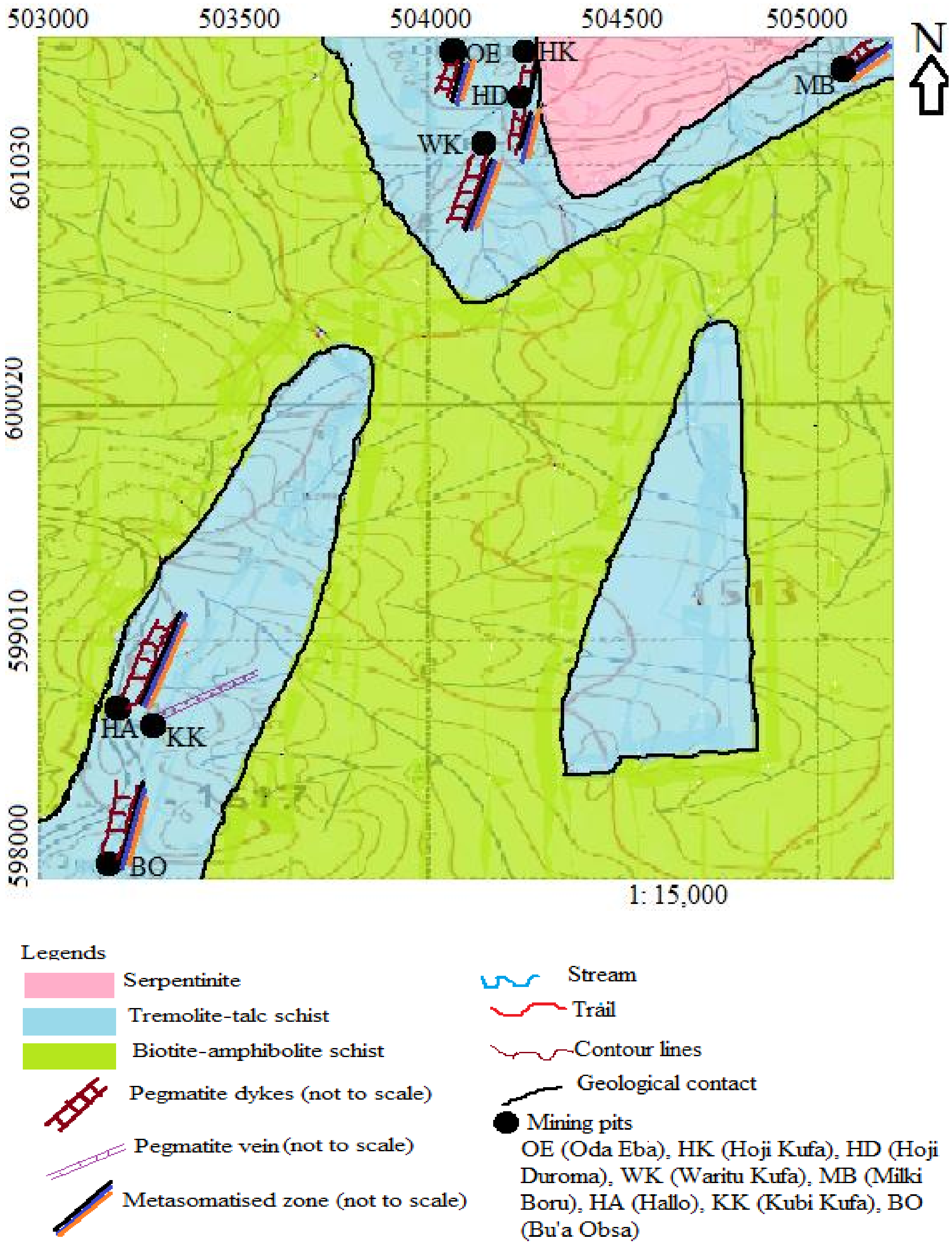


Figure 3.7 Geological map of the study area

CHAPTER FOUR

4 MINERALOGY, GEOCHEMISTRY AND GENESIS

4.1 Introduction

The chemical analyses for samples were performed in the laboratory of Ireland under the request by Australian Laboratory Services Private Limited Company (ALS-PLC). Major oxides (SiO_2, TiO_2, Al2O3, Fe_2O_3, BaO, MnO, MgO, CaO, SrO, Na_2O, K_2O, P_2O_5, Cr_2O_3, SO_3) analyses were performed by X-Ray Fluorescence, XRF (ME-XRF26) analysis. Weight based Lower Limit of Detection (LOD) for ME-XRF26 method is 0.02kg whereas the tested samples weight ranges from 0.02kg-0.46kg. The LOD for the method for oxides reaches as lower as 0.01 Wt. %. Minor, trace and Rare Earth Element (Ba, Ce, Cr, Cs, Dy, Er, Eu, Ga, Gd, Hf, Ho, La, Lu, Nb, Nd, Pr, Rb, Sm, Sn, Sr, Ta, Tb, Th, Tm, U, W, Y, Yb, Zr, Be, BeO) analyses were performed by Inductively Coupled Plasma Mass Spectrometry, ICP-MS (ME-MS81) analysis. Base metals (Ag, As, Cd, Co, Cu, Li, Mo, Ni, Pb, Sc, Ti, Zn) analyses were performed by Inductively Coupled Plasma Atomic Emission Spectrometry, ICP –AES (ME-4ACD81) analysis. Totals significantly lower than 100 wt. %, reported for several samples, are due in particular to the absence of determination for several minor elements, including Be, Li, F and V that attain rather high values which are not included in XRF analysis.

4.2 Meta-basic assemblages

Chemical analyses (Table 4.2) show that the meta-basic rocks have higher MgO content reach up to 11.5 wt. %. The chromium content (390-740 ppm) of these rocks is higher than that of metasomatized biotite schist (250ppm). Their Li content ranges from 110-430 ppm and is lower than that of biotite schist (580 ppm). The relative higher K_2O content (0.39-2.562 wt. %) is lower than that of metasomatized biotite schist (5.35 wt. %). This probably indicate the influence of K-metasomatism is higher at the contact with the pegmatite dykes and decrease away towards meta-basic. The higher Li content is due to in fluxing from the pegmatitic body. The minor and trace element analysis give distribution patterns with limited variation and their similarity to the pattern of biotite schist may suggest minor and trace element abundances have been modified by aqueous solution advancement.

Table 4.1 Mineralogical composition of meta-basic rocks from the study area (modal %)

Sample ID.	Locality	Rock type	Main composition (modal %)
HD-1	Hoji Duroma	Chlorite schist; greenish, fine-course grained, schistose; chlorite shows well-developed parallel alignment	Chlorite (flaky) 85; Opaque (Fe-oxide, xenoblastic) 15; Biotite (flaky) trace; Quartz (xenoblastic) trace
HA-1	Hallo	Chlorite-talc schist; brownish-greyish-greenish, fine-medium grained, schistose; talc and chlorite show a strong well-developed parallel alignment	Talc (flaky) 83; Chlorite (flaky) 15; Opaque (Fe-oxide, xenoblastic) 2
WK-1	Waritu Kufa	Tremolite-talc schist; greenish gray, fine-course grained, schistose; talc and tremolite show well-developed parallel alignment	Talc (flaky) 80; Tremolite (xenoblastic) 15; Opaque (Fe-oxide, xenoblastic) 5
MB-1	Milki Boru	Epidote-quartz-hornblende schist; dark greyish, fine-medium grained, schistose; hornblende, quartz, epidote, plagioclase and sphene show well-developed parallel alignment	Hornblende (xenoblastic) 40; Quartz (xenoblastic) 20; Pilagioclase (xenoblastic) 15; Epidote (xenoblastic) 20; Sphene (xenoblastic) 5; opaque (xenoblastic) trace

Table 4.2 Chemical composition of meta-basic rocks from the study area

Sample ID.	Major elements (Wt. %)		Minor and trace elements (ppm)				base metals (ppm)	
HA-1	SiO2	54.56	Ba	740	Rb	279	Ag	0.5
	TiO2	1.22	Ce	189.5	Sm	12.7	As	5
	Al2O3	12.06	Cr	740	Sn	12	Cd	0.5
	Fe2O3	6.97	Cs	61.9	Sr	353	Co	32
	BaO	0.09	Dy	5.39	Ta	2.2	Cu	4
	MnO	0.08	Er	1.98	Tb	1.03	Li	430
	MgO	11.5	Eu	2.25	Th	20.7	Mo	1
	CaO	2.09	Ga	19.9	Tm	0.22	Ni	406
	SrO	0.05	Gd	9.68	U	7.03	Pb	17
	Na2O	1.06	Hf	14.7	V	54	Sc	13
	K2O	2.56	Ho	0.83	W	2.2	Ti	10
	P2O5	1.32	La	79.9	Y	24	Zn	556
	Cr2O3	0.12	Lu	0.14	Yb	1.2		
	SO3	0.01	Nb	26.1	Zr	560		
	LOI	5.78	Nd	78.1	BeO	69		
	Total	99.7	Pr	22.7	Be	25		
MB-1	SiO2	47.22	Ba	70.9	Rb	7.8	Ag	0.5
	TiO2	1.22	Ce	13.9	Sm	2.48	As	5
	Al2O3	17.15	Cr	390	Sn	1	Cd	0.5
	Fe2O3	12.52	Cs	1.32	Sr	344	Co	47
	BaO	0.02	Dy	4.77	Ta	0.2	Cu	102
	MnO	0.21	Er	3.18	Tb	0.7	Li	110
	MgO	5.49	Eu	0.86	Th	0.71	Mo	1
	CaO	12	Ga	19.3	Tm	0.42	Ni	109
	SrO	0.05	Gd	3.68	U	0.16	Pb	3
	Na2O	2.93	Hf	1.5	V	261	Sc	39
	K2O	0.39	Ho	1.06	W	2	Ti	10
	P2O5	0.03	La	7	Y	27.6	Zn	94
	Cr2O3	0.08	Lu	0.43	Yb	2.64		
	SO3	0.01	Nb	8.6	Zr	49		
	LOI	0.7	Nd	7.5	BeO	8		
	Total	100.15	Pr	1.79	Be	3		

4.3 Biotite schist

This unit is the interphase unit at pegmatite and meta-basic contact. Invasion of pegmatite/pegmatite driven aqueous solution influenced its composition due to in-fluxing of elements. Therefore, it mimics altered composition of the meta-basic (parental source) due to fluxing overprint. Its K_2O, Ga and Nb content is higher than meta-basic. This justifies that the metasomatized zone is enriched in pegmatite components than meta-basic and have an average composition between pegmatite and meta-basic. Widely dispersed minor apatite has been identified in these rocks in addition to chlorite. The relative higher content of CaO and P_2O_5 in these rocks might be due to introduction of apatite. Chlorite might be due to alteration of biotite and hornblende.

Table 4.3 Mineralogical composition of biotite schist from the study area (modal %)

Sample ID.	Locality	Rock type	Main composition (modal %)
HD-2	Hoji Duroma	Quartz-biotite schist; dark gray, fine-course grained, schistose; biotite and quartz show a strong well-developed parallel alignment	Biotite (flaky) 90; Quartz (xenoblastic) 5; Opaque (iron oxide) 5 Accessory beryl, apatite and chlorite

Table 4.4 Chemical composition of biotite schist from the study area

Sample ID	Major elements (Wt. %)		Minor and trace elements (ppm)				base metals (ppm)	
HD-2	SiO2	29.21	Ba	350	Rb	1475	Ag	0.5
	TiO2	0.28	Ce	37.7	Sm	6.33	As	5
	Al2O3	10.7	Cr	250	Sn	8	Cd	0.5
	Fe2O3	5.66	Cs	364	Sr	329	Co	41
	BaO	0.06	Dy	5.64	Ta	70.4	Cu	1
	MnO	0.1	Er	3.57	Tb	0.86	Li	580
	MgO	15.55	Eu	2.16	Th	3.75	Mo	1
	CaO	16.7	Ga	31.9	Tm	0.52	Ni	505
	SrO	0.04	Gd	5.41	U	6.51	Pb	7
	Na2O	0.41	Hf	0.2	V	83	Sc	7

	K2O	5.35	Ho	1.17	W	3	Ti	10
	P2O5	12.6	La	16	Y	38	Zn	200
	Cr2O3	0.04	Lu	0.63	Yb	3.65		
	SO3	0.01	Nb	62.8	Zr	2		
	LOI	2.52	Nd	20.3	BeO	33		
	Total	99.4	Pr	5.02	Be	12		

4.4 Pegmatite dykes

The pegmatites have higher values of SiO_2 (74.78 wt. %), Al_2O_3 (14.30 wt. %), Rb/Sr (25.76) and depletion in CaO (0.38 wt. %), Y (29.80 ppm), Zr (11.00 ppm), Ba (12.00 ppm), Sr (8.50ppm). These characteristics are attributed to incongruent melting of a muscovite-rich meta-sedimentary source (Scaillet et al., 1990, Harris and Inger, 1992 as sited in Lawrence W. Snee, 1996). The relatively higher values of Cr (30.00 ppm), V (9ppm), and Fe_2O_3 (0.98 wt. %) suggest that the pegmatites experienced greater interaction with the surrounding meta-basic. This is also supported by alteration of the meta-basic rocks as well.

Table 4.5 Mineralogical composition of pegmatites from the study area (modal %)

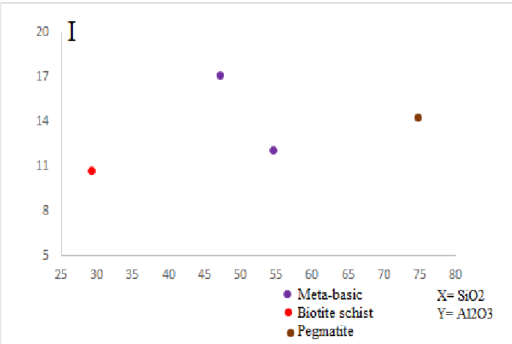
Sample No	Locality	Rock type	Main composition (modal %)
KK-1	Kubi Kufa	Quartz (quartz core); Gray colored, fine - course grained, granoblastic texture, matrix mainly composed of quartz and minor plagioclase, muscovite and opaque mineral.	Quartz (xenoblastic) 94-100; opaque (xenoblastic) 3; Plagioclase (xenoblastic) 2; Muscovite (tiny-flaky) 1
BO-1	Bu’a Obsa	Pegmatite; Greyish, granoblastic texture, course grained; matrix composed of plagioclase, quartz and muscovite	Plagioclase (xenoblastic) 65; quartz (xenoblastic) 30; muscovite (flaky) 4; opaque (xenoblastic) trace
HK-1	Hoji Kufa	pegmatite; Light gray colored, fine – medium grained	Quartz (xenoblastic) 62; Plagioclase (xenoblastic)35; Biotite (flaky) 3;

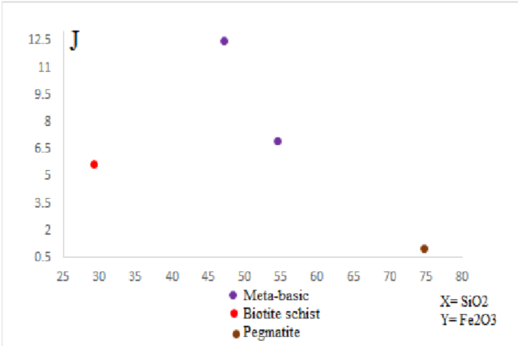
		Granoblastic texture with quartz, Plagioclase and biotite matrix	Trace opaque (Fe-oxide, xenoblastic)
OE-1	Oda Eba	pegmatite; Light gray colored, fine – medium grained Granoblastic texture.	Plagioclase (xenoblastic) 69; Quartz (xenoblastic) 30; opaque (Fe-oxide, xenoblastic) 1; Trace Muscovite (tiny flaky)
HA-2	Hallo	Pegmatite; Light greyish, course grained, slightly schistosed due to deformation at the contact; Muscovite, plagioclase and quartz show certain parallel alignment	Muscovite (flaky) 69; plagioclase (xenoblastic) 20; quartz (xenoblastic) 10; opaque (xenoblastic) 1

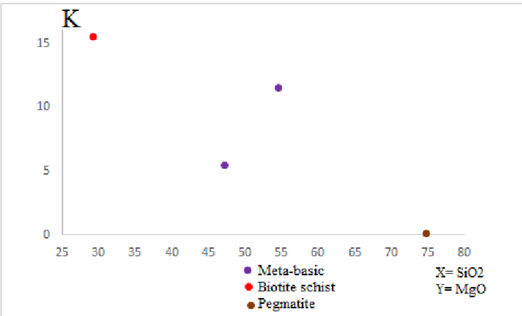
Table 4.6 Chemical composition of pegmatite from the study area

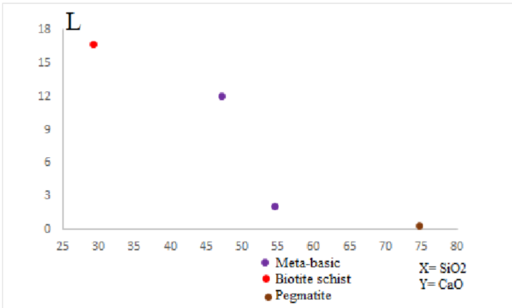
Sample ID	Major elements (Wt. %)		Minor and trace elements (ppm)				Base metals (ppm)	
HK-1	SiO2	74.78	Ba	12	Rb	219	Ag	0.5
	TiO2	0.03	Ce	16.6	Sm	4.55	As	5
	Al2O3	14.3	Cr	30	Sn	7	Cd	0.5
	Fe2O3	0.98	Cs	8.55	Sr	8.5	Co	1
	BaO	< 0.01	Dy	5.51	Ta	3.9	Cu	1
	MnO	0.02	Er	2.25	Tb	0.98	Li	160
	MgO	0.1	Eu	0.03	Th	12.65	Mo	1
	CaO	0.38	Ga	39.1	Tm	0.43	Ni	1
	SrO	< 0.01	Gd	3.99	U	3.95	Pb	32
	Na2O	4.86	Hf	0.9	V	9	Sc	21
	K2O	2.65	Ho	0.84	W	3	Ti	10

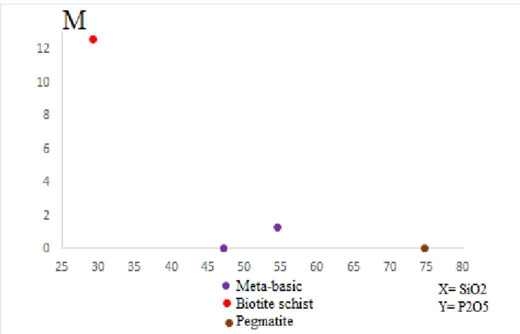
	P2O5	0.01	La	6.2	Y	29.8	Zn	22
	Cr2O3	< 0.01	Lu	0.5	Yb	3.58		
	SO3	< 0.01	Nb	106.5	Zr	11		
	LOI	0.71	Nd	8.7	BeO	33		
	Total	98.82	Pr	2.1	Be	12		

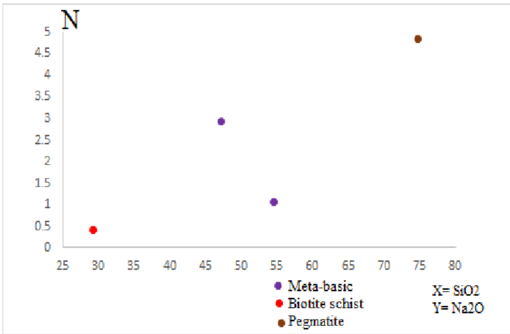












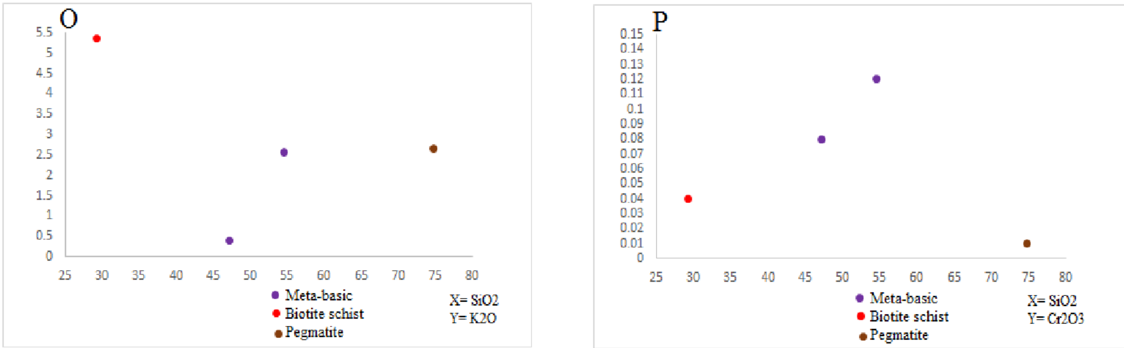
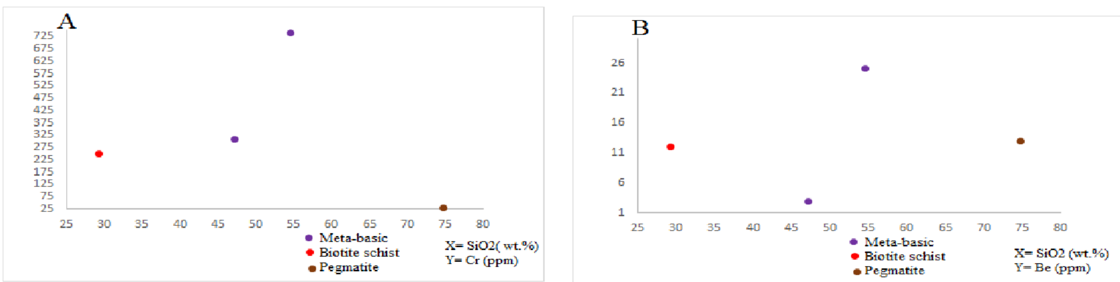


Figure 4.1 Harker-type variation diagrams showing SiO_2 variation for various major/minor element oxides (in wt. %), I) Al_2O_3, J) Fe_2O_3, K) MgO, L) CaO, M) P_2O_5, N) Na_2O, O) K_2O and P) Cr_2O_3 for meta-basic, metasomatised biotite schist and pegmatite.

Major oxides Al_2O_3, Fe_2O_3, CaO and Na_2O (Figure 4.1; I, J, L and N) show negative correlation whereas MgO, P_2O_5, K_2O and Cr_2O_3 (Figure 4.1; K, M, O and P) show positive correlation for meta-basic rocks as silica increase. The major oxides (MgO, CaO, K2O and P2O5) versus silica for biotite schist, pegmatite and meta-basics indicate their advanced concentration in biotite schist. This might be due to introduction of these components into the metasomatised zone from both meta-basics and pegmatites. Whenever the major oxides versus silica show positive correlation for meta-basic rocks, the same oxides versus silica for biotite schist show higher value of the oxides. Biotite schist also shows advanced concentration of oxides those have higher ratio to silica in the pegmatite. The positive correlation of MgO and SiO2 for meta-basic rocks is due to alteration of meta-basic rocks particularly because of pegmatite intrusion. This is also marked by the positive correlation of the P2O5 and K2O with silica in meta-basic rocks. These components are enriched in pegmatites and fluxing of them into the meta-basic rocks yield their positive correlation with silica in the meta-basic rocks. The variation diagram also suggests that formation of metasomatised zone biotite schist involves addition of MgO, Ca, P_2O_5 and K_2O and removal of SiO_2, Fe_2O_3, Na_2O and Cr_2O_5. Moreover, the value of pegmatite as compared to meta-basic variation suggests that Fe_2O_3 and Cr_2O_3 value in pegmatite (Figure 4.1; J and P) gates advanced from the surrounding meta-basic



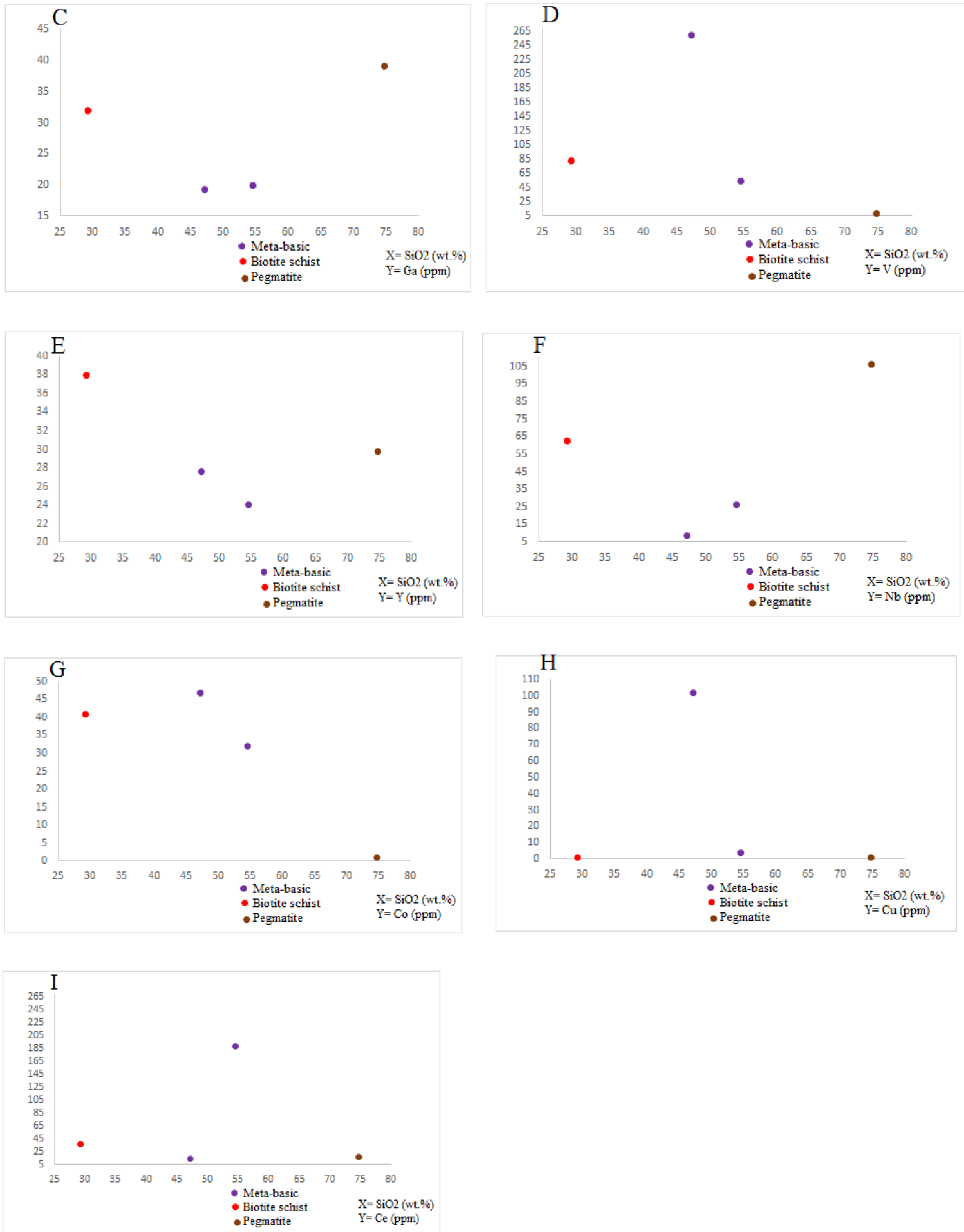


Figure 4.2 Harker-type variation diagrams showing SiO_2 variation for various minor/trace elements (in ppm), A) Cr, B) Be, C) Ga, D) V, E) Y, F) Nb, G) Co, H) Cu and I) Ce for meta-basic, metasomatised biotite schist and pegmatite.

Minor/trace elements V, Y, Co and Cu (Figure 4.2; D, E, G and H) show negative correlation whereas Cr, Be, Ga, Nb and Ce (Figure 4.2; A, B, C, F and I) show positive correlation for meta-basic rocks as silica increase. The minor/trace elements versus silica distribution pattern indicate that the pattern for biotite schist is intermediate for both pegmatite and meta-basics. This might be attribute to the enrichment of metasomatised zone with these elements after pegmatite emplacement. The higher value in Be for one meta-basic rock sample (Figure 4.2; B) might suggest the source of Be for emerald mineralization could also be meta-basics itself in addition to the pegmatites.

4.5 Apatite, beryl-apatite inclusion and emerald

4.5.1 Apatite

As it has been already described in chapter three, quartz-apatite veins are distributed in the biotite schist and at the margins of pegmatite dykes. The trace elemental composition of metasomatized zone biotite schist lies between those of apatite and pegmatite. The biotite zone is metasomatized zone due to thermal and derivative brine solution effect of pegmatite intrusions in to meta-basic. biotite schist enrichment in trace elements therefore is due to in fluxing of these elements in to meta-ultramafic via brine solution transportation. The lighter elements which are not able to join in the early crystallizing phase will be taken further in the brine solution and precipitated in veins those cross-cut meta-basic. Apatite has trace elements concentration closer to alteration zone biotite schist than to pegmatite. Since the formation of biotite schist is due to introduction of pegmatite or its fluids in to meta-basic, and this resulted in enrichment in pegmatitic components, similar trace element concentration anomaly is therefore resulted. Although, apatite trace element concentration anomaly shows similarity with both pegmatite and biotite schist, it has closer value to that of alteration resulted biotite schist. Therefore, the apatite of the area is not directly precipitated from pegmatite alone. Rather, it is related to either hydrothermally reactivated apatite which initially exist as a magmatic accessory in parental basic rocks or crystallization from Ce and Y enriched aqueous solutions at the contact of pegmatites and meta-basic. The Ce and Y positive anomaly in the apatite chemistry (Figure 4.4; E and I) is inherited from fluids enriched in these elements. Moreover, the chemical signature of alteration resulted biotite schist also has positive anomaly of these elements. For apatite is an early crystallizing phase than beryl, we can also conclude, the beryl of the area is not a result of a single phase pegmatite-meta-basic interaction. Rather, it results from both thermal alteration at the contact for contact beryl, and brine solution propagation (metasomatism) into meta-basic rocks for beryl formed within the metasomatized meta-basic rocks.

Table 4.7 Chemical composition of apatite

Sample ID	Major elements (Wt. %)		Minor and trace elements (ppm)				Base metals (ppm)	
KK-2	SiO2	2.98	Ba	13.9	Rb	57	Ag	<0.50
	TiO2	0.01	Ce	102.5	Sm	13.3	As	<5.00
	Al2O3	0.09	Cr	40	Sn	1	Cd	2.9
	Fe2O3	0.54	Cs	14.55	Sr	1600	Co	1
	BaO	0.03	Dy	12.85	Ta	4.3	Cu	2
	MnO	0.42	Er	8.11	Tb	2.05	Li	30
	MgO	0.95	Eu	5.73	Th	10	Mo	1
	CaO	52.3	Ga	3.2	Tm	1.24	Ni	36
	SrO	0.2	Gd	12.95	U	30.2	Pb	21
	Na2O3	0.09	Hf	22.8	V	7	Sc	2
	K2O	0.19	Ho	2.81	W	1	Ti	<10.00
	P2O5	39.5	La	44.2	Y	80	Zn	12
	Cr2O3	0.01	Lu	1.42	Yb	8.12		
	SO3	<0.01	Nb	4	Zr	103		
	LOI	0.53	Nd	49.4	Be	601		
	Total	98.72	Pr	12.75	BeO	1670		

4.5.2 Beryl with apatite inclusions

The beryl in thin lenticular quartz veins/vein-lets and pegmatite veins at the pegmatite meta-basic contact has inclusions of apatite and biotite. The thermal and brine solution invasion into meta-basic rocks delivered Be necessary for emerald mineralization. The invasion of these variables also reactivated magmatic apatite which already exist in parental basic rocks. After the invading brines liberated Cr from meta-basic, beryl and apatite co-precipitated at the contact zone of pegmatite and biotite schist. The chemistry of these beryl therefore is influenced by the chemistry of included apatite showing higher value of CaO and P_2O_5. The contribution of beryl composition is evident from the higher value of beryllium (601ppm) in the average composition of apatite. Pegmatite, biotite schist, apatite and beryl-apatite inclusion shows positive anomaly of Ce, Nd, Gd and Y (figure 4.8, 4.9 and 4.10). This indicates that biotite schist, apatite and beryl-apatite inclusions are resulted from fluids enriched in these components.

Table 4.8 Chemical composition of beryl-apatite inclusion

Sample ID	Major elements (Wt. %)		Minor and trace elements (ppm				Base metals (ppm)	
BO-2	SiO2	32.85	Ba	59.4	Rb	58.9	Ag	<0.50
	TiO2	< 0.01	Ce	31.5	Sm	4.33	As	<5.00
	Al2O3	10.45	Cr	300	Sn	1	Cd	1.3
	Fe2O3	1.21	Cs	80.04	Sr	990	Co	3
	BaO	< 0.01	Dy	4	Ta	5.7	Cu	1
	MnO	0.17	Er	2.85	Tb	0.64	Li	120
	MgO	1.62	Eu	1.92	Th	5.98	Mo	<1.00
	CaO	24	Ga	15.4	Tm	0.47	Ni	33
	SrO	0.12	Gd	3.99	U	9.24	Pb	17
	Na2O3	2.78	Hf	1.2	V	21	Sc	13
	K2O	0.33	Ho	0.87	W	1	Ti	<10.00
	P2O5	17.65	La	14.3	Y	27.8	Zn	33
	Cr2O3	0.04	Lu	0.61	Yb	3.45		

	SO3	< 0.01	Nb	4.8	Zr	8			
	LOI	1.02	Nd	14.7	Be	> 1000			
	Total	92.25	Pr	4.02	BeO	>2800			
OE-2	SiO2	38.4	Ba	47.3	Rb	50.9	Ag	<0.50	
	TiO2	0.01	Ce	147	Sm	21.7	As	<5.00	
	Al2O3	10.8	Cr	490	Sn	1	Cd	<0.50	
	Fe2O3	2.96	Cs	139	Sr	496	Co	2	
	BaO	0.02	Dy	22.7	Ta	3	Cu	2	
	MnO	0.12	Er	14.4	Tb	3.56	Li	150	
	MgO	1.66	Eu	4.52	Th	4.2	Mo	1	
	CaO	21.1	Ga	16.6	Tm	1.87	Ni	20	
	SrO	0.06	Gd	22.2	U	6.72	Pb	12	
	Na2O3	2.18	Hf	0.2	V	34	Sc	24	
	K2O	0.21	Ho	4.91	W	3	Ti	<10.00	
	P2O5	15.55	La	61.8	Y	123	Zn	38	
	Cr2O3	0.08	Lu	1.86	Yb	12.15			
	SO3	<0.01	Nb	2.5	Zr	5			
	LOI	1.07	Nd	77.2	Be	>1000			
	Total	94.28	Pr	18.8	BeO	>2780			

4.5.3 Emerald

The Kilkile emerald is characterized by higher MgO (0.26-4.08 wt. %) and Fe_2O_3 (1.39-2.18 wt. %) and lower Cr_2O_3 (0.01-0.09 wt. %) contents. Its SiO_2 content ranges from 59.13-61.79 wt. % while CaO and P_2O_5 content ranges from 1.25-3.85 and 0.02-1.88 wt. % respectively. The emerald of Kilkile area shows minor and trace elements anomaly nearly similar to metasomatized biotite schist and pegmatite. The geochemical signatures of Kilkile emerald shows that emerald of the area is associated with interaction of pegmatite and meta-basic rocks. Sometimes, when the source of both Cr and Be remains the same, emerald mineralization may not associated with pegmatites. But, in the case of Kilkile, emerald has geochemical anomaly nearly similar to pegmatite. Therefore, the Kilkile emerald is pegmatite related, where pegmatite was delivering Be necessary for emerald mineralization. Biotite schist resulted from metasomatized meta-basic rocks also has geochemical anomaly similar to emerald. This attributes for the role of meta-basic in emerald mineralization by delivering Cr. The Kilkile emerald has low SiO_2 and Cr_2O_3 and high Al_2O_3, Fe_2O_3, MgO, CaO and K_2O as compared to its Zambian counterpart (figure 4.13). Although, higher iron and magnesium content is the typical properties of schist hosted emerald, the relatively higher value of iron and magnesium in the kilkile emerald might attribute for the highly ferromagnesian nature of the meta-basic rocks or aggressiveness of the brine solution in liberating Mg and Fe from meta-basic rocks. The major, minor and trace elements anomaly of the minerals of Kilkile area (emerald, apatite and beryl-apatite inclusion) showing synonymous pattern (figure 4.14 and 4.15) justifies their mode of formation which involves elemental fluxing and removal into or from the constituting components.

Table 4.9 Chemical composition of emerald from the study area

Sample ID	Major elements (Wt. %)		Minor and trace elements (ppm				Base metals (ppm)	
HD-3	SiO2	59.13	Ba	77.5	Rb	641	Ag	<0.50
	TiO2	0.02	Ce	2.2	Sm	0.55	As	<5.00
	Al2O3	18.52	Cr	120	Sn	18	Cd	<0.50
	Fe2O3	1.76	Cs	134	Sr	809	Co	10
	BaO	0.02	Dy	0.51	Ta	14.8	Cu	<1.00

	MnO	0.04	Er	0.35	Tb	0.1	Li	530
	MgO	4.08	Eu	0.41	Th	1.17	Mo	<1.00
	CaO	3.85	Ga	48.1	Tm	0.07	Ni	61
	SrO	0.12	Gd	0.76	U	1.99	Pb	18
	Na2O	7.05	Hf	2.7	V	11	Sc	1
	K2O	1.7	Ho	0.12	W	1	Ti	<10.00
	P2O5	1.88	La	0.8	Y	3	Zn	59
	Cr2O3	0.02	Lu	0.03	Yb	0.34		
	SO3	<0.01	Nb	44.6	Zr	15		
	LOI	1.27	Nd	2.1	Be	527		
	Total	99.5	Pr	0.44	BeO	1460		
HA-3	SiO2	59.94	Ba	120	Rb	89	Ag	<0.50
	TiO2	0.02	Ce	3	Sm	0.1	As	<5.00
	Al2O3	20.13	Cr	600	Sn	2	Cd	<0.50
	Fe2O3	2.18	Cs	123.5	Sr	845	Co	5
	BaO	0.01	Dy	<0.05	Ta	16.3	Cu	<1.00
	MnO	0.03	Er	0.03	Tb	0.02	Li	180
	MgO	2.52	Eu	0.21	Th	3.09	Mo	<1.00
	CaO	2.56	Ga	30.4	Tm	0.01	Ni	52
	SrO	0.1	Gd	0.11	U	1.78	Pb	17
	Na2O	5.51	Hf	6.2	V	32	Sc	18
	K2O	0.52	Ho	<0.01	W	1	Ti	<10.00
	P2O5	0.02	La	2	Y	0.4	Zn	58

	Cr2O3	0.09	Lu	<0.01	Yb	<0.03		
	SO3	<0.01	Nb	9.2	Zr	29		
	LOI	1.38	Nd	1	Be	>1000		
	Total	95.05	Pr	0.29	BeO	>2780		
WK-2 Waritu Kufa	SiO2	61.79	Ba	20.9	Rb	156	Ag	<0.50
	TiO2	0.01	Ce	7	Sm	0.91	As	<5.00
	Al2O3	17.75	Cr	40	Sn	<1.00	Cd	<0.50
	Fe2O3	1.39	Cs	541	Sr	97.8	Co	2
	BaO	<0.01	Dy	0.43	Ta	0.2	Cu	2
	MnO	0.02	Er	0.15	Tb	0.08	Li	1710
	MgO	0.26	Eu	0.41	Th	0.13	Mo	1
	CaO	1.25	Ga	22.1	Tm	0.02	Ni	9
	SrO	0.01	Gd	0.74	U	0.66	Pb	7
	Na2O	1.09	Hf	<0.20	V	9	Sc	1
	K2O	0.07	Ho	0.07	W	1	Ti	<10.00
	P2O5	0.85	La	2.7	Y	1.7	Zn	561
	Cr2O3	0.01	Lu	<0.01	Yb	0.07		
	SO3	<0.01	Nb	0.8	Zr	3		
	LOI	2.17	Nd	3.9	Be	>1000		
	Total	86.76	Pr	0.94	BeO	>2780		

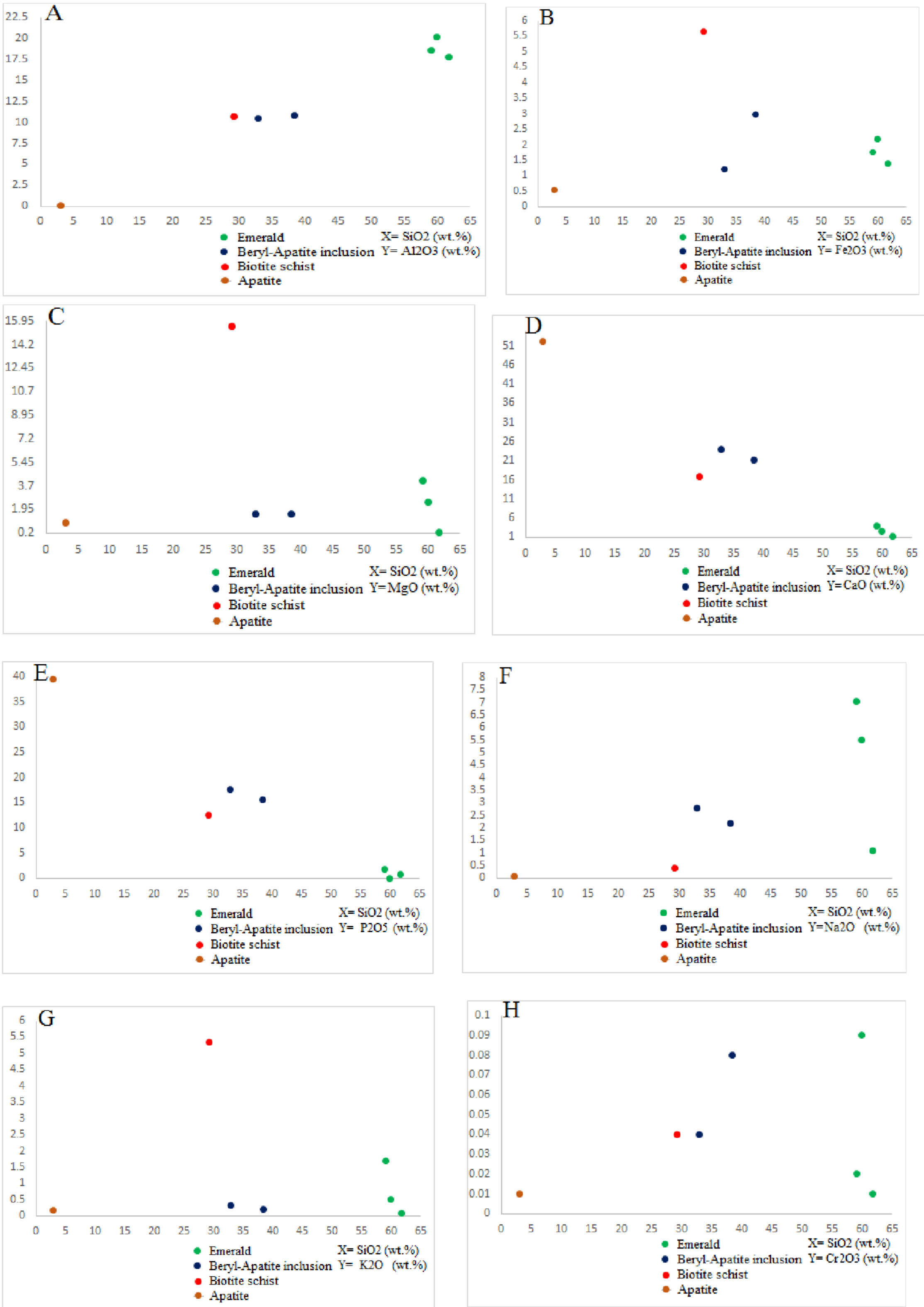
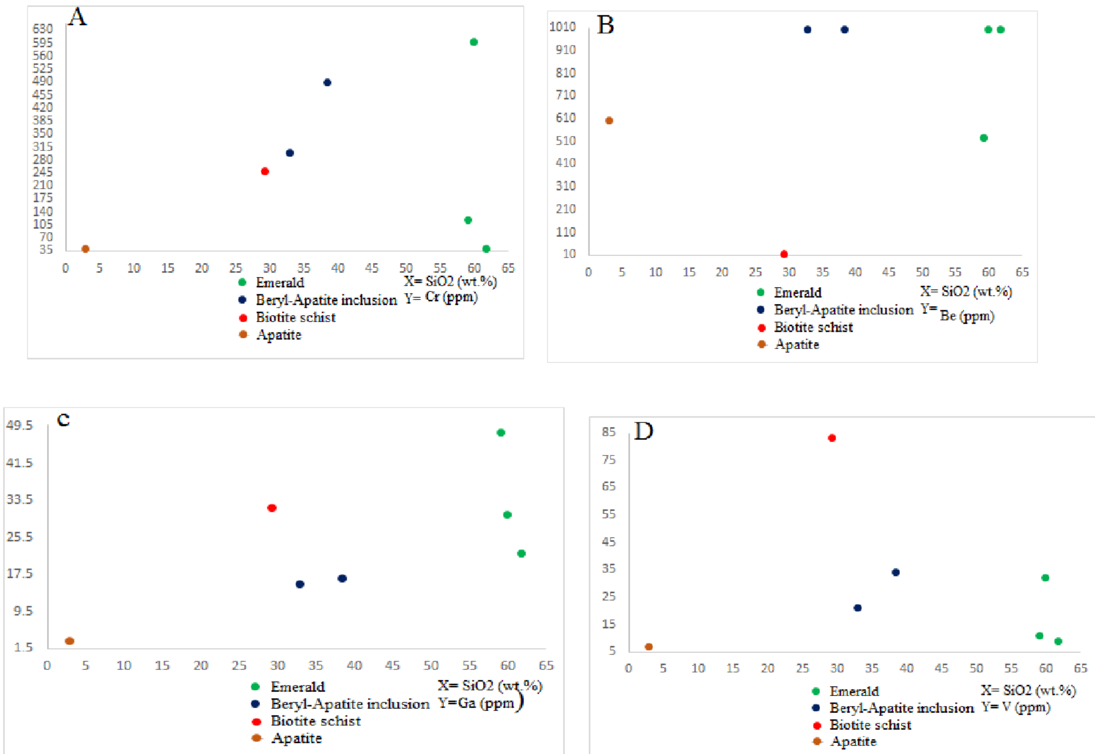


Figure 4.3 Harker-type variation diagrams showing SiO_2 variation for various major/minor element oxides (in wt. %), A) Al_2O_3, B) Fe_2O_3, C) MgO, D) CaO, E) P_2O_5, F) Na_2O, G) K_2O and H) Cr_2O_3 for emerald, beryl-apatite inclusion, biotite schist and apatite

Major oxides Al_2O_3, Fe_2O_3, MgO and Cr2O3 (Figure 4.3; A, B, C and H) shows positive silica correlation for beryl-apatite inclusions. On contrary to these CaO, P2O5, Na_2O and K_2O (Figure 4.3; D, E, F and G) shows negative correlation. In either conditions the distribution pattern of biotite schist is more consistent with that of beryl-apatite inclusion than to emerald. This might be due to high Cao which enter into the apatite structure in the meta-basic rocks than Cr/V that inter into emerald structure.



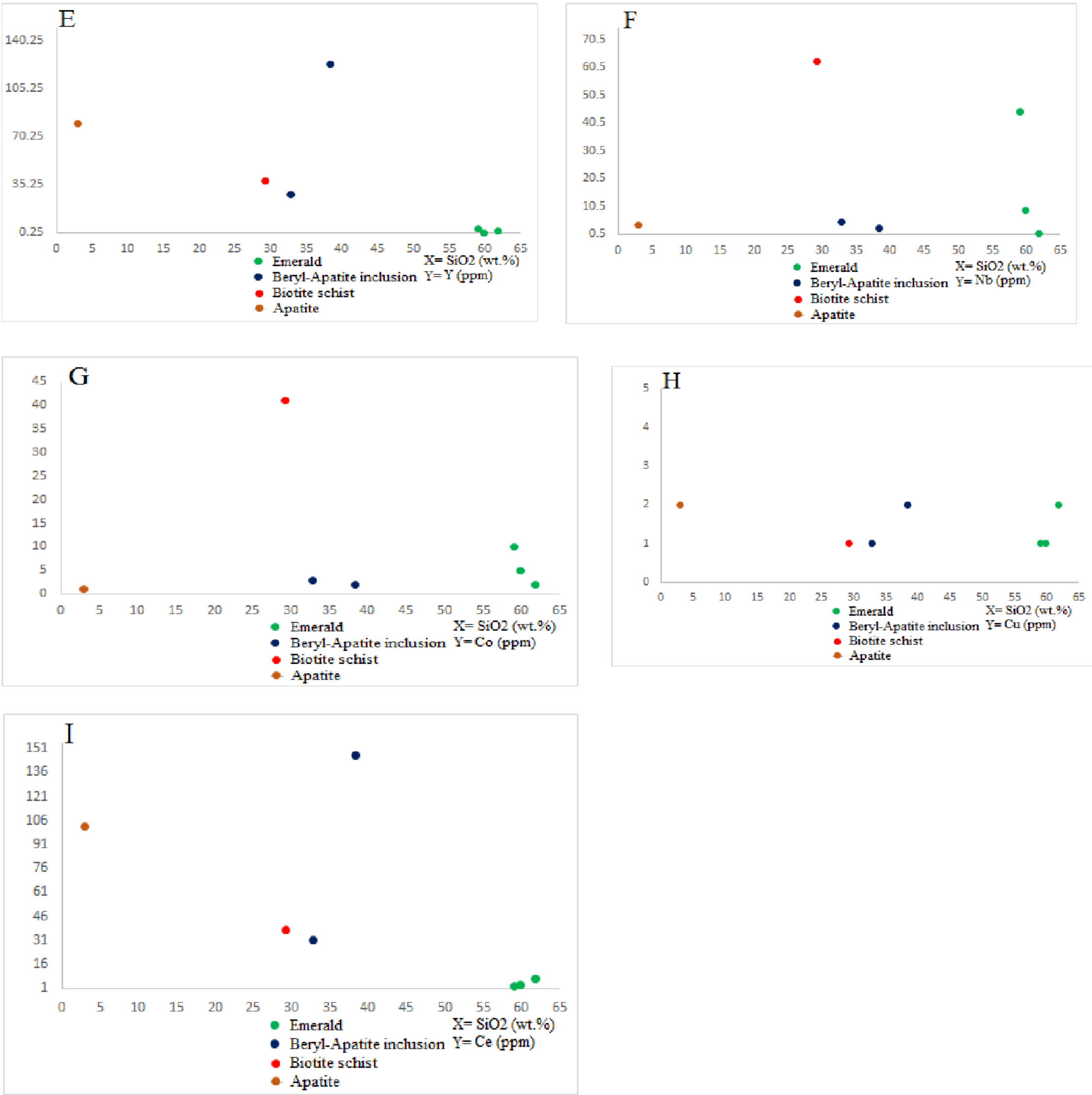


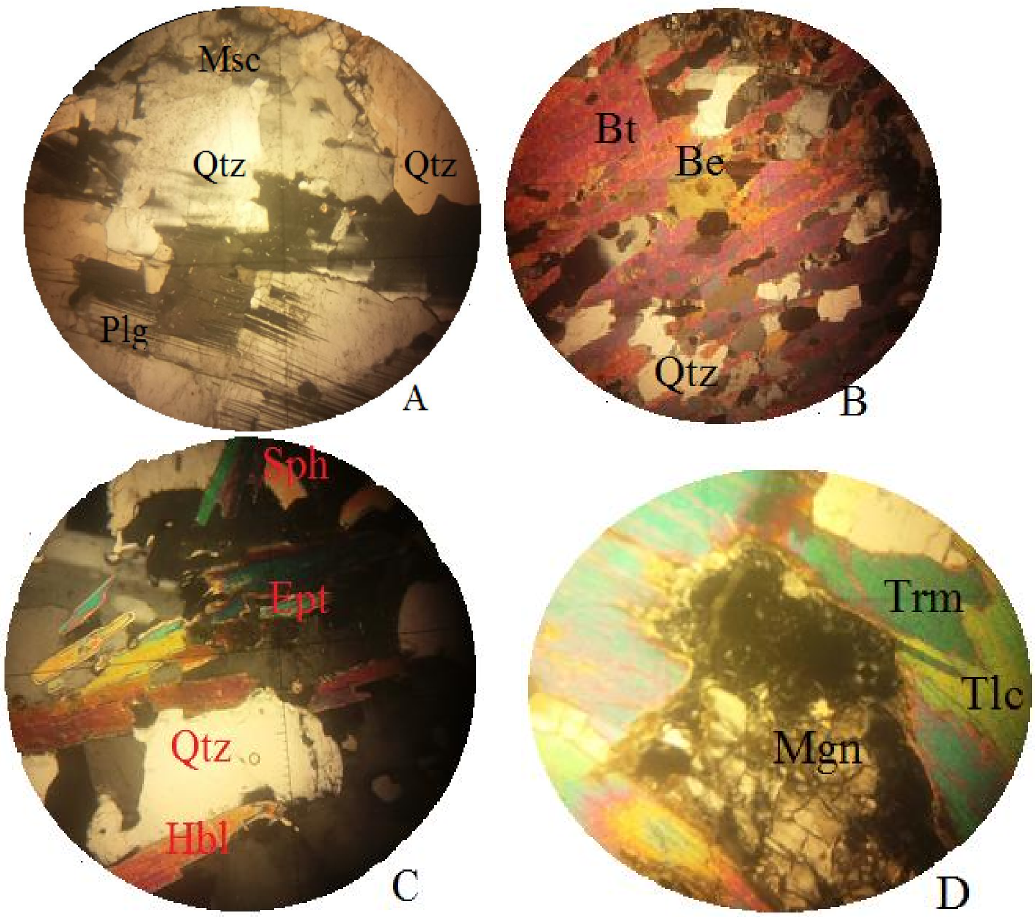
Figure 4.4 Harker-type variation diagrams showing SiO_2 variation for various minor/trace elements (in ppm), A) Cr, B) Be, C) Ga, D) V, E) Y, F) Nb, G) Co, H) Cu and I) Ce for emerald, beryl-apatite inclusion, biotite schist and apatite

The same as major oxides minor/trace elements distribution patter for biotite schist is related to beryl-apatite inclusion than to emerald. Since apatite is the early crystallizing phase, the majority of these elements might join into this phase before joining the later forming emerald. The minor/trace elements those enriched in emerald than in beryl-apatite inclusion might be those which could not able to be stable in the early crystallizing phase. Generally, the introduction of pegmatites and their derivative brine solution into meta-basic rocks changed the average composition of the contact zone meta-basic rocks. Therefore, the resulted contact (metasomatized) zone rocks possessed average composition of pegmatite and meta-basic interaction. As a fact of this, minerals and gems formed within the metasomatized zone are the result of pegmatite meta-basic interaction. The justification for this argument is that the major and trace elements variation pattern of the of metasomatized zone rock (biotite schist), meta-basic and pegmatites are synonymous. The elemental comparison between metasomatized zone biotite schist and pegmatite shows the enrichment of biotite schist with CaO, P_2O_5, K_2O, Ga, Nb, Be and depletion in Na_2O and SiO2. This indicates that the transformation of meta-basic rocks into biotite schist involves a major influx of CaO, P_2O_5, K_2O, Ga, Nb, Be and the removal of Na_2O and SiO_2. The higher concentration of CaO and P_2O_5 within metasomatized zone biotite schist might be due to reactivated (hydrothermal resulted) apatite from apatite formed in the original ultramafic rocks as a magmatic accessory. This is justified from relatively high concentration of CaO and P_2O_5 in meta-basic rocks. The metasomatized unit thus shows enrichment in pegmatitic components and apatite due to the above mentioned reasons.

Table 4.10 Major elements composition of Ethiopian Kilkile versus Zambian emerald, data for Zambian emerald taken from (Calligaro et al., 2000 as sited in Antonin et al., 2004)

	Ethiopia			Zambia										
	1	2	3	1	2	3	4	5	6	7	8	9	10	11
SiO2	59.13	59.94	61.79	62.79	62.75	61.91	61.42	62.07	63.81	63.8	63.91	58.92-65.72	62.23	64.9
TiO2	0.02	0.02	0.01	-	-	-	-	-	-	-	-	-	-	
Cr2O3	0.02	0.09	0.01	0.37	0.55	0.25	0.12	0.1	0.31	0.4	0.08	0.23-0.53	0.33	-
Al2O3	18.52	20.13	17.75	12.08	11.24	12.23	11.59	11.98	15.07	14.6	18.88	13.63-15.26	15.41	14.7
Fe2O3	1.76	2.18	1.39	1.07	1.35	0.96	1.01	1.17	1.03	0.9	0.69	0.47-0.97	0.11	-

MnO	0.04	0.03	0.02	-	-	-	-	-	-	-	0.08	-	0.02	-
MgO	4.08	2.52	0.26	2.28	2.9	2.07	2.58	2.3	2.04	2.3	0.83	1.84 - 2.34	0.76	2.3
CaO	3.85	2.56	1.25	0.06	0.07	0.03	0.05	0.04	0.03	0	0.96	-	0.31	0.05
Na2O	7.05	5.51	1.09	1.77	1.99	1.71	1.88	1.85	1.86	1.9	1.45	0.96 - 1.65	2.63	1.9
K2O	1.7	0.52	0.07	0.08	0.06	0.06	0.07	0.07	0.04	0	0.01	-	2.89	0.06



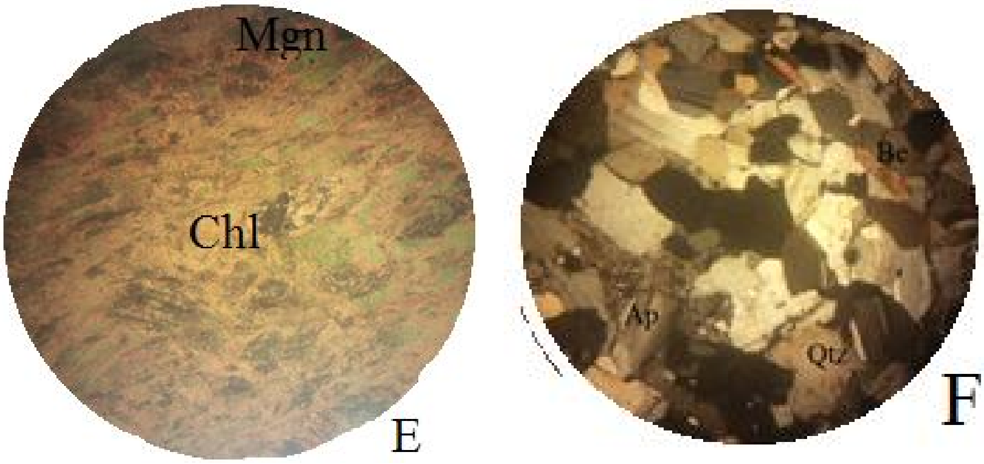


Figure 4.16 XPL, cross polarized (magnification, 10x10) photographs of major rock forming and accessory minerals from the study area, A) pegmatite, B) biotite schist, C) epidote-quartz-hornblende schist, D) tremolite-talc schist, E) chlorite schist, F) quartz-apatite-beryl vein. Bt = biotite, Ept = epidote, Qtz =quartz, Hbl = hornblende, Trm = tremolite, Tlc = talc, Chl = chlorite, AP = apatite, Be =beryl, Sph = sphene, Mgn = magnetite.

4.6 Genesis and exploration criterion

4.6.1 Genesis

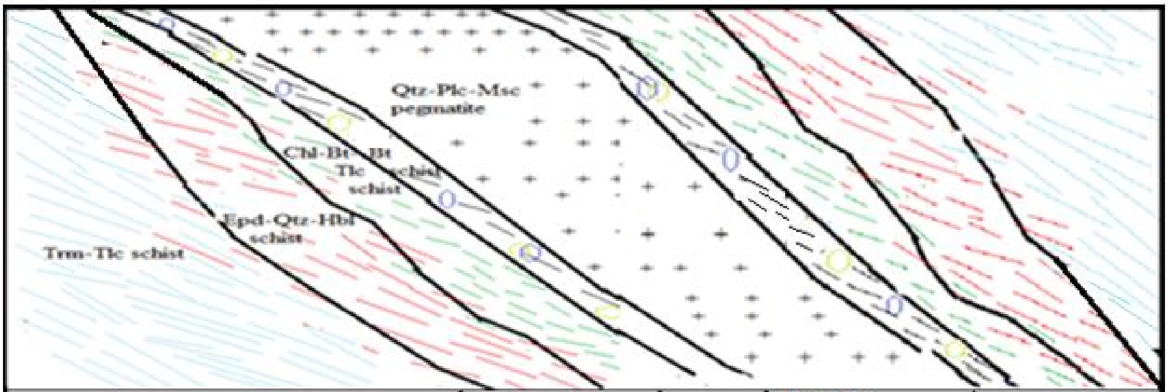
Although many researches undergone as far as schist hosted emerald occurrences are concerned, no single model has been formulated so far as it has been already explained in the literature reviews portion of this document.

The first model suggested by Fersman (1929) as sited in Zwaan (2006) correlates emerald formation with single stage contact metamorphism at pegmatite- meta-mafic-ultramafic contact.

The second model correlates emerald formation with multiphase process during low-grade regional metamorphism. In this model emeralds formed by reactions that took place during deformation of the rocks and low-grade regional metamorphism. Emeralds are not found in association with pegmatite (although pegmatites may occur in the region). More recently, (Zwaan, 2006) proposed a new model by considering the role of shearing in emerald mineralization. In this model emerald is formed by two successive events; Syn-tectonic metasomatism at the contact of ultramafic rocks and rare-element pegmatites followed by shear focused late stage magmatic/hydrothermal activity.

In the present study at Kilkile area, structural field relationship, mineralogical and geochemical analyses results have been used to interpret the genesis of emerald mineralization.

As far as mineralogy and geochemistry are concerned; the mineralogy and chemistry of pegmatites, emerald hosting metasomatized biotite schist, meta-basic rocks, gangue minerals and emerald suggests emerald mineralization at Kilkile area is related to interaction between meta-basic rocks and pegmatites or their derivative brine solutions. As it has been described in the previous sections, the chemical analyses results for the above mentioned rocks and minerals show similar anomaly of major and trace elements. The emerald hosting metasomatized biotite schist is the product of the interaction between meta-basic and pegmatites or their fluids. The gangue minerals (apatite and quartz) and emerald formed at the contact of the pegmatites and metasomatized biotite schist or within the biotite schist then are the result of concentrations of their constituent elements in the metasomatized zone up on the expenses from the altered meta-basic and the pegmatites. This suggestion is supported by the comparison of major and trace elements concentration anomaly between- 1) meta-basic, metasomatized biotite schist and pegmatites 2) emerald or gangue minerals and metasomatized biotite schist. Frist if metasomatized biotite schist is the result of interaction between pegmatites or their derivative brine solutions and meta-basic rocks; the major and trace elemental concentration anomaly of the biotite schist shows similarity to the anomaly of both the pegmatites and meta-basic. Second if the gangue minerals or emerald of the area are the product of the interaction, then their chemical anomaly shows similarity to biotite schist, this is because of the fact that the minerals are the product of interaction in a similar fashion to that of biotite schist itself. The major element composition of emerald plots between the major element composition of pegmatite and biotite schist. This indicates that the emerald formation is resulted from interaction of pegmatites and schist. Biotite schist and emerald as it is clearly observed from the figures above have almost overlapping composition. This is a typical identity of emerald resulted from interaction of pegmatites and adjacent meta-basic rocks. Two things to be clear here is that the similarity of the emerald and schist in major elemental concentration and the average concentration value of the emerald as compared to the pegmatites and schist. Therefore, evidence for Kilkile emerald for its pegmatite-meta-basic interaction origin is supported in its major elemental concentration in addition to the minor and trace elemental concentration.



0	35	5	10-100 at core	Qtz
0	0	0	0-69	Plc
5	15-Feb	5	0-3	Opm
0	0	0	0-69	Msc
0	0-15	90	0-3	Bt
80	83	0	0	Tlc
15	0	0	0	Trm
	85	0	0	Chl
	40	0	0	Hbl
	20	0	0	Epd
	5	0	0	Sph

Figure 4.17 mineralogical transition pattern between major rocks of the mapping area (not to scale), Qtz=quartz, Plc=plagioclase, Opm=opaque mineral, Msc=muscovite, Bt=biotite, Tlc=talc, Trm=tremolite, Chl=chlorite, Hbl=hornblende, Epd=epidote, Sph=sphene

Mineralogical composition of pegmatites, metasomatized biotite schist and meta-basic rocks also suggest the transition nature in each zone. The mineralogy of pegmatite is dominated by quartz and plagioclase with considerable amount of muscovite and trace amounts of opaque minerals and biotite. In metasomatized biotite schist, the percentage of quartz decreases to 5% with biotite increase to 90% and opaque minerals to 5%.

The unit next to metasomatized biotite schist is composed of intercalations of chlorite schist, epidote-quartz-hornblende schist and chlorite-talc schist. Chlorite is assumed to be the result of alteration of biotite and hornblende into chlorite. The peripheral thickest unit in the mapping area is tremolite-talc schist. Therefore, mineralogical variation pattern within these units will also help in suggesting the emerald of the area as meta-basic –pegmatite interaction resulted. As far as structural field relationship is concerned, localization of mineralization along major brittle and ductile structures and gangue minerals/emerald crystal growth pattern with respect to the emplaced pegmatite dykes (controlled by regional structures) suggest that emerald mineralization is resulted from pegmatite meta-basic interaction. (1) Most emerald crystals grow normal to the contact between pegmatites and meta-basic, attribute to crystallization parallel to the cooling front (2) emerald mineralization is mostly confined to the contact (3) where pegmatite/quartz veins are sheared, emerald mineralization is highly confined to the openly folded portions of the boudinaged, swelled and pinched vein. This is found adjacent to the slightly sheared country rocks where shearing is manifested by tightly folded hairline quartz veinlet. The pegmatite in Kilkile area is genetically related to dome and lens shaped differentiated pegmatite intrusions along discrete N-S fault and shear system. These post Orogenic intrusives form horizontal stratigraphic arrangement with meta-basic suite and follows N-S trending regional fault and shear system. Therefore these N-S trending structures are believed to have controlled the localization of pegmatites and emerald mineralization. In addition to these N-S trending principal regional faults and shear systems, there are two younger fault systems trending NE-SW and NW-SE. therefore, the intersection of these younger fault systems with the principal regional structures appears to be the most favorable site for the emplacement of the late stage differentiated pegmatites and emerald mineralization along the contact with the meta-basic.

From mineralogical, geochemical and structural field relationships the genesis of Kilkile emerald can be summarised as follows:-

1. Basic rocks derived from upper mantle metamorphosed to green-schist facies
2. The exhumation of the meta-basic rocks accompanying the N-S trending kenticha deep-seated fault
3. The development of NE-SW and NW-SE trending younger fault systems due to exhumation
4. The intrusion of granitic massifs (1x7km, lenticular stoke) in to the N-S trending principal fault and newly developed younger faults
5. During the post tectonic granitic magma development , the injection of pegmatites in to the deep seated fault and other simultaneously developed structures within the meta-basics
6. The development of metasomatised biotite schist due to mineral exchange between pegmatite and meta-basic rocks
7. Emerald mineralization at pegmatite-meta-basic contact due to contact metamorphism and in openly folded, swelled, boudinaged and pinched shear driven structures due to hydrothermal brine solution metasomatism.

4.6.2 Exploration criterion

Emerald mineralization at Kilkile area is confined to the contact of pegmatite dykes and meta-basic rocks. The meta-basic rocks of the area are tremolite -talc schist, chlorite-schist, biotite-talc schist and epidote-quartz-hornblende schist. The pegmatite dykes are confined in north–south trending faults with few exceptions trending NW-SE and NE-SW. The N-S trending main structures (faults and veins) are the result of Kenticha deep-seated fault which comprises branches that separate the principal fault blocks marked by discontinuous chains of Serpentinite and elongated zones of silica-magnesium and iron siliceous metasomatized zones. This fault is the principal cause in bringing the meta-ultramafic rocks from the considerable depth to their recent position. Moreover, shearing in the area is displayed by boudinaged, pinched and swelled quartz vein-lets exposed on the major rocks of the area. Therefore, the N-S trending major geological structures, their intersections with NE-SW and NW-SE younger structures and sheared, boudinaged, pinched and swelled quartz veins manifested on the surface of the country rocks are the major areas that might suggest the emerald mineralization spots.

CHAPTER FIVE

5 MINING AND PROCESSING

5.1 Introduction

Mining for gems by methods of tunneling, shafts, and other means employed in deep mine workings is rarely carried on. In the first place, gems do not often occur in definite veins as do the precious metals, being more commonly irregularly distributed in pockets through the rock. In the second place, little really systematic mining of gems is carried on. As a rule, the occupation is, or has been, a rather desultory one. A find of a few good stones leads to temporary search and exploration, lasting for a few years perhaps, then the work proves no longer profitable and is abandoned until new finds arouse new hope and revive the industry. The element of fortune, good and bad, seems to prevail more largely in the mining of gems than in even that of the precious metals. In gem-mining, as in that for gold and silver, great labor and little reward go side by side with little labor and great reward. Moreover, the distribution of gems is exceedingly irregular, and their market price varies within wide margins, from circumstances of fashion, supply and general financial conditions. The distribution of gems through a rock or gravel matrix is not usually uniform. The gems more commonly occur in pockets, where crystallization of minerals has taken place about a fissure or open cavity the minerals are more likely to be clear and free from inclusions than where formed in the mass of the rock itself (Oliver Cummings Farrington, 1903). Regarding the influence of increase of depth upon the distribution and quality of the gem minerals, no principles have been established as yet. It is known that veins of amethysts, for instance, have turned entirely colorless on penetrating below the surface, so that a valuable stone became with depth worthless. On the other hand, improvement in color and quality of stones below the surface, as compared with those above, may often be reasonably expected, since the latter are more exposed to disintegration and weathering, and the fading effects of light. In the mining of gems in a small way the amateur is likely to make the mistake of resorting to the use of too much powder or other explosive. While the rough work of exploration may wisely be carried on by means of blasting, the actual removal of the mineral from the matrix should usually be performed, where possible, by picks and chisels, in order to avoid the shattering and breaking of pieces suitable for gems, which often happens in blasting. Many fine gems have been lost through carelessness in the work of mining, and while not all losses of this kind can be avoided, with care and patience they can be reduced to a minimum.

5.2 Mining operation at Kilkile area

The Southern Ethiopian; "Saba Boru district" emerald has acquired the general name called "Kilkile Emerald" due to the fact that the Kilkile locality was the first in producing emerald from Ethiopia. As a matter of this fact the present study also used this general name as its title. However, the emerald occurrences are not limited to the Kilkile area alone in the Saba Boru district of Southern Ethiopia. During field mapping for the purpose of this study, emerald occurrences are also encountered in areas like- Mi'o Gala Arba, Hallo, Hoji Duroma, Milki Boru, Oda Eba, Kubi Kufa, Haro Kufa, Bu'a Obsa and Waritu Kufa. Apart from Mi'o Gala Arba (due to some administrative problems) all other mining and exploration pits were sampled and described. Mining licencing is conducted by two means (Associations and SME- Small and Micro Enterprises) at Saba Boru district based on; capital, professionals, machineries and participating shareholders.

The Associations (Mi'o Gala Arba, Hallo, Hoji Duroma, Milki Boru, and Waritu Kufa) are those who have; good initial capital, limited mining professionals (mining geologists and mine surveyors) and limited machineries (bulldozers, excavators, dump trucks). The shareholders in associations are local peoples earning (40%) and investors earning (60%) of the profit. Investors cover the running costs of the mining work. The gem quality crystals collected by associations are presented to global markets after some levels of faceting and treatments.

The Small and Micro Enterprises (Oda Eba, Kubi kufa, Haro Kufa and Bu'a Obsa) obtained their initial capital from regional government as a means of loan, lack mining professionals and machineries. The shareholders in these sectors are limited to the locals of the area from where the mineral is exploited. As a means of job creation; the Oromia National Regional Government distributed the mineral occurrence localities for the youths of the area, who sell their products to the local markets (mineral brokers or associations).

In general, emerald mining at Saba Boru district is not following the professional mining disciplines- reconnaissance, exploration, feasibility, mine development and other studies are not conducted for the deposit. Mostly; the associations those following semi mechanized mining by themselves are not following professional mining (pits have no design, mineral grades are not calculated). Local miners hunt for larger and purer crystals only- causing destroyed emerald crystals distributed all over the area (in the pits and its surroundings) in the district. Even if they find the high quality crystals, the methods that they are using to take it out is destructive; causing the crystals for cracking, shattering and total destruction even.

5.2.1 Factors controlling mining at Kilkile area

5.2.2 Geology and structure

The major rock units constituting the geology of Kilkile area includes; meta-basic assemblages, alteration zone (metasomatized) biotite schist, pegmatite dykes/veins and quartz-apatite-veins/vein-lets as it has been already described in the former chapters. The thickness, strength, composition, moisture and tectonic structures of the units are conditions those control mining at Kilkile area. The stability of the units are highly influenced by their compositional (micro) structures. As it is presented in table 5.1 most of the units at Kilkile area are composed of flaky minerals. The inter-granular cohesion of the flaky minerals is low and this contributes for weak slope stability. The units composed of xenoblastic minerals have better slope stability as it is evidenced in the unit composed of xenoblastic epidote, quartz, hornblende and sphene. Therefore, since mineralogical compositions of most units composing the area have flaky mineral aggregates, the entire of the area experienced weak slope stability. The thickness of emerald hosting biotite schist and adjacent meta-basic rocks rarely exceed five metres. The minimum thickness of the units reduce excavation cost even after failure. However, the thinness of the unit also affects stability by reducing inter-granular attraction force. The emerald hosting biotite schist have folded and sharp contact with pegmatite dykes and meta-basic rocks respectively. The folded contact with pegmatite dykes contribute for good stability on the excavation slope whereas sharp contact with meta-basic contribute for sliding along excavation.

The structures that control the mining operations at Kilkile area are the combination of planar and linear structures resulted from primary (nature of the rock) and secondary processes. Both primary and secondary structures primarily attain nearly similar orientations, north- south striking and east/southeast dipping. The N-S plunging lineations produced due to intersections of axial planes of shear and crenulation cleavage and the axis of folds produced due to folding of S1 foliation are the major linear structures. Lithological contact zone joints, tectonic resulted E-W trending fractures, foliations and schistose foliation resulted from bands of micas parallel to the foliation planes are the major planar structures controlling mining at Kilkile area. The joint orientation, pattern, frequency, opening, filling and extension established at the contacts and within the units also play significant role on the stability. Most of the joints oriented N-S, have systematic pattern, repeated (frequent), about 1cm open, void to rarely fill with fibrous minerals like talc and 5-15cm long. The N-S orienting joints contribute for weak slope stability along N-S by causing sliding and allowing surface water percolation. However, their systematic pattern might reduce water circulation by reducing permeability (they are not effectively porous). Moreover, the joints are void or fill by fibrous minerals which contribute for slope instability.

Table 5.1 compositional parameters controlling mining at Kilkile are, Qtz=quartz, Plc=plagioclase, Opm=opaque mineral, Msc=muscovite, Bt=biotite, Tlc=talc, Trm=tremolite, Chl=chlorite, Hbl=hornblende, Epd=epidote, Sph=sphene, Apt=apatite, Brl= beryl

Lithological units	Thickness	Stability	Composition wt.%	Compositional structures
Chl-Tlc schist	10cm	Weak	Talc (83) Chl (15) Opaque (2)	Flaky Flaky Xenoblastic
Chl schist	10cm	Weak	Chlorite (85) Opaque (15) Trace biotite Trace quartz	flaky Xenoblastic Flaky Xenoblastic
Edt-Qtz-Hbl Schist	5m	Good	Hornblende (40) Quartz (20) Plg (15) Epidote (20) Sphene (5) Opaque (trace)	Xenoblastic Xenoblastic Xenoblastic Xenoblastic Xenoblastic Xenoblastic
Trm-Tlc schist	>3km	Weak	Talc (80)	Flaky

			Tremolite (15) Opaque (5)	Xenoblastic Xenoblastic
Qtz-Bt schist	20-30cm	Weak	Biotite (80) Quartz (20) Opaque (trace)	Flaky Xenoblastic Xenoblastic
Pegmatite dykes	1-5m	Good	Quartz (62) Plagioclase (35) Biotite (3) Opaque (trace)	Xenoblastic Xenoblastic Flaky Xenoblastic

Table 5.2 structural parameters controlling mining at Kilkile are

No	Measured structure	Dip	Dip directio
1	foliation	60	136
2		25	100
3		70	120
4		35	140
5		55	90
6		30	110
7	joints	20	105
8		17	145
9		15	150
10		10	130
11		20	85
12		15	160
13		30	165
14		25	80
15		35	170
16	lineation	plunge	plunge direction
17		40	350
18		50	50
19		40	10
20		30	340
21		45	135
22		20	122

23		10	355
24		20	180
25		15	170
26		20	160
27		15	185
28		25	170
29		80	20

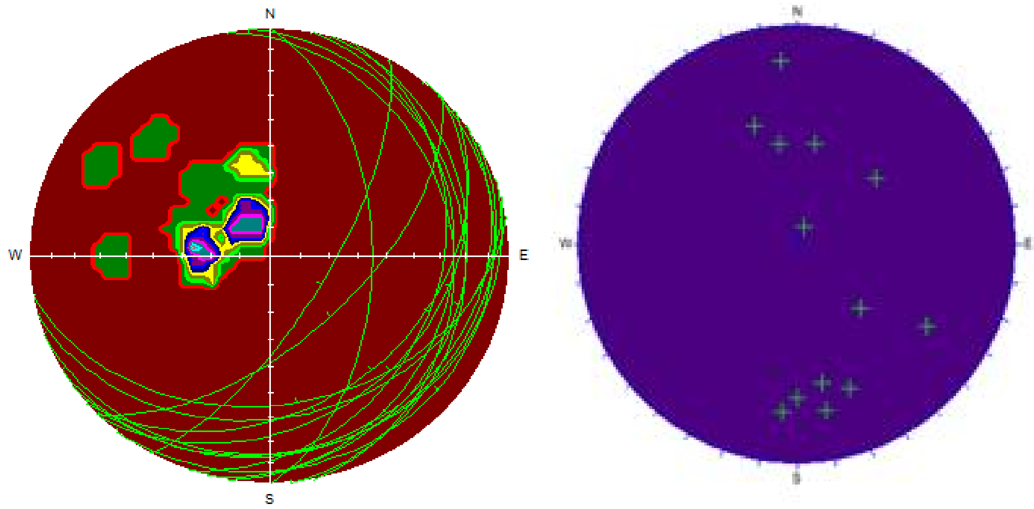


Figure 5.1 equal area, lower hemisphere, Stereonet presentation of planar (left) and linear (right) structures at Kilkile area

As it is clearly observed on figure 5.1 most of the planar and linear structures are easterly or south-easterly dipping/plunging. The strike length of the pegmatite dykes resulted emerald mineralization is N-S, calling for N-S mining progress. Mining progress in N-S direction requires pit opening with benches cut normal to the dipping/plunging of the country rocks. This condition causes planar mode of failure along west.

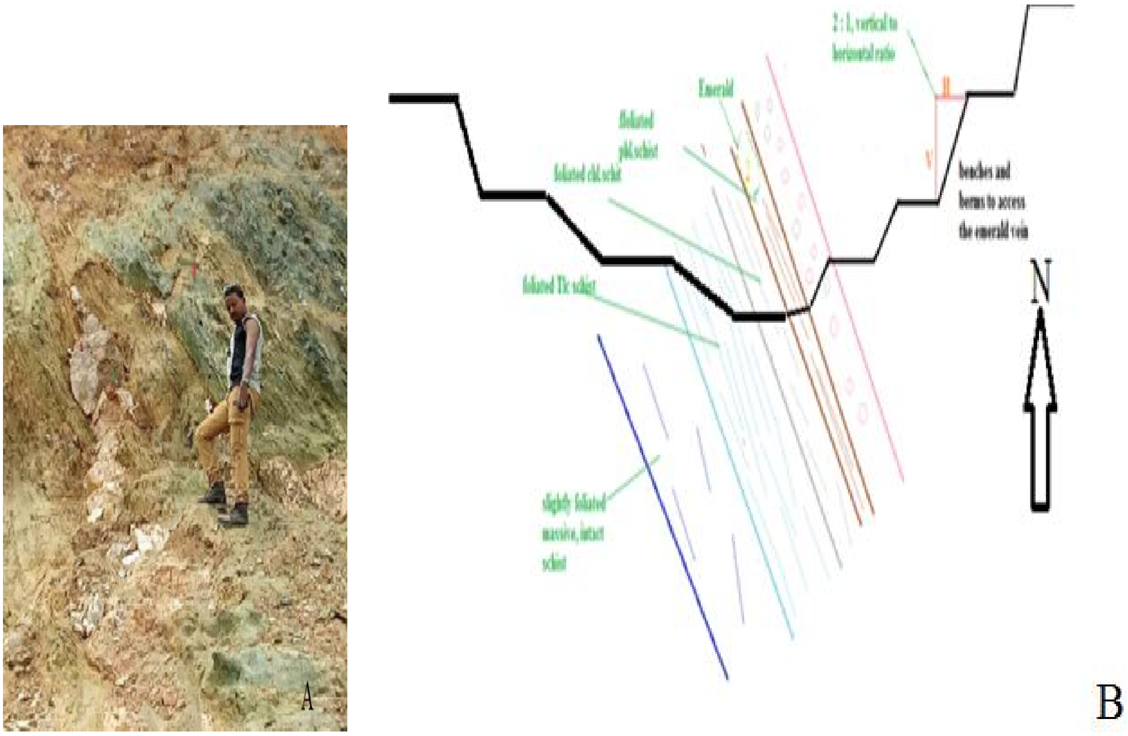


Figure 5.2 A) Actual mining pit B) Sketched illustration of mining procedure in use at Kilkile area (not to scale)

The benches of the pit are normal to the dip/plunge of the structures (figure 5.2). This condition juxtapose the western berms of the pit on the dip/plunge of the structures and facilitate planar mode of failure along the berm. On the other hand, even if the bench of the pit is normal to the dip/plunge of the structures, the eastern berm of the pit is at acute angle to the structures. Therefore, the western berm of the pit is exposed to failure than that of the eastern berm in the existing mine at Kilkile area.

The longer axis of the emerald crystal is also oriented in the east/southeast direction; calling for mining to proceed in the direction normal to its long axis (mining proceed in N-S), for the safer crystal collection by minimal destruction. This confronts with the challenge arising from east/southeast dipping structures that falls to the pit. This challenge observed in almost all units, but very prominent in the talc unit due to its softness, easily slide to the pit.

As it is mentioned in the introductory section of this chapter, the establishment of mine design for gemstone mining is less common except for few mines in the world for which the reserve is known. This is mainly due to erratic distribution of gems in the rock matrix, they may disappear while mining is in progress. The emerald occurrence at kilkile area is not exceptional, the abandoned pits are due to their lack in emerald. However we can at least propose some methods to follow while mining to prevent sudden accidents that may possibly happen from rock mass wasting.

The 2: 1, vertical to horizontal ratio in use is similar in all rock units and both sides of the pit. As it has been already described above different units have different stability conditions due to their composition, dip/plunge amount, thickness and others. If we for example consider talc and schist units, they have similar orientation but, talc is soft and easily sliding rock than schist of the area as it is also recognized at the field. The other thing that we need to consider is the thickness of the units. The highly unstable talc unit is thicker than the schist units (very thin, tens of centimeters). Therefore, post fall clearing can also be possible in the case of schist but, not for the thicker talc unit. Moreover, the western berm of the pit is unstable due to its overlapping with the geological structures as already mentioned. Therefore, these all reasons call for vertical to horizontal ratio variation during pit opening. The most unstable units and the western side of the pit requires lower vertical to horizontal ratio, whereas the relatively stable units and eastern side of the pit comparably require larger vertical to horizontal ratio. From these we can conclude that, the unstable tremolite-talc schist, biotite-talc schist, biotite schist and chlorite schist requires lower vertical to horizontal ratio whereas the relatively stable epidote-quartz-hornblende schist requires larger vertical to horizontal ratio. Except tremolite-talc unit (elevated excavation cost), units calling for lower ratio are thin and hence excavation cost might be reduced to reasonable stage. With no existing calculated reserve for kilkile emerald, the use of convenient mine design (requires the knowledge of thickness, length and depth of mineralization) is not sounding. What can be here is only for the safety of the locals and small associations.

5.3 Processing

Processing for a mineral begins at the stage of mine development; appraisal of appropriate instrumentation and technology for best recovery, selection of best method/s of mining for exhaustive exploitation, arrangement of hauling and stoking sites for save (non-extravagant) handling etc. Gem minerals are very sensitive; any cracking, shattering or exposure to deteriorate might reduce the need for them or make them useless even. Therefore, mining and processing for gems requires due attention, from which emerald is not exceptional.

At Kilkile area, the way emerald is taken out from its host rocks and separated from gangue minerals is prone to cracking and shattering. The local collectors focus on the larger crystals and on doing so they expose the smaller crystals for destruction by hammering and chipping.

Moreover, the associations using machineries like chain excavators and bulldozers crush the crystals while moving during excavations. Therefore, both for local collectors and associations, it is required to follow some procedures for safe exploitation with minimum acceptable destruction.

5.3.1 Processing procedures proposed for Kilkile emerald

First, excavation of overburden should carried out with greater care by bulldozers. After overburden removal, wheel excavators are better than chain excavators to cut the benches and berms of the pit since wheel excavators produce minimum vibration and destruction to the surrounding emerald hosting rocks. Following the pit slope development, hand collection of courser crystals using sharp hammer tips with digging normal to the long axis of the crystal is suggested. Hand collection should proceed for any visible green crystals as much as possible. After being sure that hand collection is impossible, for the crystals are invisible and enclosed in rock matrixes, all rocks expected to host emerald should be collected and stoked. The stoked rock mass should then transported to the processing plant. In the processing plant, the size of the crystals lower than hand collected should be allowed to pass through washing/screening trummel. After the crystal passes a grizzly stage (size determined after identifying the minimum size that can be hand collected), it is broken by a jaw crusher (at a minimum damage as much as possible). The crushed rock is then washed, sized and vibrating screens further separate the material into specific size ranges. After passing the crusher and the screens, the matrixes is divided into various sizes of schist, emerald and pegmatite. After size classification; the separation of pegmatite, schist and emerald materials from each other is carried out through density separation. The pegmatite has a density close to 2.6 g/cm, whereas the schist is around 2.9-3.0 g/cm, and the emerald around 2.75 g/cm. Therefore, the density used to separate them should be very critical due to their similarity in density. In many emerald mines of the world ferrosilicon mixed with magnetite is used as density liquid with operational density of 2.5 g/cm maximum. Besides, the above described options to recover emerald safely, trial processing is very important since different variables drive the process in unexpected direction.

Chapter six

6 Conclusions and Recommendations

6.1 Conclusions

The biotite schist, emerald, beryl-apatite inclusion and pegmatite geochemical relationships favours the pegmatite- meta-basic interaction origin for Ethiopian Kilkile emerald. The higher value in Be for one meta-basic rock might infer the possibility of meta-basic rocks as a source for Be in addition to pegmatites. However, the occurrence of emerald mainly at the contact of metasomatised zone strength the pegmatite source for Be than meta-basics. The higher Be value in one meta-basic rock sample could also be due to aqueous solution propagation into meta-basics from the emplaced pegmatite. Emerald mineralization is hosted in biotite schist resulted from fluxing exchange of pegmatitic components with magnesia enriched meta-basic rocks. The genesis of Kilkile emerald passed through series processes – metamorphism of basic rocks to green-schist facies, exhumation of the meta-basic rocks accompanying the N-S trending Kenticha deep-seated fault, development of NE-SW and NW-SE trending younger fault systems due to exhumation, intrusion of granitic massifs (1x7km, lenticular stoke) in to the N-S trending principal fault and newly developed younger faults, injection of pegmatites in to the deep seated fault and other simultaneously developed structures within the meta-basics during the post tectonic granitic magma development resulted development of metasomatised biotite schist due to interaction and ion exchange between pegmatite and meta-basic rocks and emerald mineralization at pegmatite-meta-basic contact. Therefore the classic model for emerald mineralization also holds in the case of Kilkile. The poorness in chromium in the emerald might be due to less chromium content of the meta-basic rocks or less fluxing of pegmatitic fluids to liberate it from the meta-basics. The operating pits at the Kilkile area are aligned on tremolite- talc schist and biotite-amphibolite schist contact, where pegmatites intruded into the tremolite-talc schist. The mining progress direction is N-S following the general strike length of the pegmatite bodies. While mining, the safer emerald crystal collection direction is also compliant with the strike length. However, this is challenged from slope collapse particularly from the weaker units and western berm of the mining pits as it overlaps with the dipping direction of the rock masses. Therefore, The most unstable units and the western side of the pit requires lower vertical to horizontal ratio, whereas the relatively stable units and eastern side of the pit comparably require larger vertical to horizontal ratio. The dykes or veins of Kilkile area follows the major regional structures initiated by Kenticha deep-seated fault. Therefore, emerald mineralization is also expected in other areas beside, the operational pits. Comparable to its Zambian counterpart the Kilkile emerald is iron rich, chromium poor and have more apatite inclusion as a solid inclusion.

6.2 Recommendations

The followings are highly recommended.

A. Fluid inclusion in gems reduce color enhancement and strength, thereby make cut for gems difficult. Therefore, the type and nature and distribution of fluid inclusion require further study

B. In most schist hosted emeralds, emeralds have internal compositional zonings. These zonings dictate the cut direction during faceting. Furthermore enhancement for color and strength also depend on gemological properties and hence further gemological study is recommended

C. Three dimensional exploration (thickness, strike length and depth) of the pegmatite dykes and veins in order to enable grade and reserve calculation and mining design appraisal

D. The pit location and geological map suggests that mineralization is following a regional structures and the intersections of these fractures. Therefore, further exploration in the areas of the intersections of these structures is also recommended

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