VALUE ADDITION TO LOCAL VEIN QUARTZ IN PRODUCING INDUSTRIAL GRADE SILICA

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Thesis submitted in partial fulfillment of the requirements for the degree Master of Science

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February 2018

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ABSTRACT

Applications of high-purity quartz as a raw material in high-tech industry are numerous. A few of them includes semiconductors, microchips, industrial integrated circuits, high temperature lamp tubing, optical fibers, chemically reinforced glass and solar silicon cells. Sri Lanka is rich in quartz mineralization with an abundance of major vein quartz deposits with purity levels over 99.5% of SiO_2. Developing high-tech products requires considerable capital investment, expertise and advance processing technologies which are lacking in developing countries like Sri Lanka. Thus leading to export raw quartz with enforced size reduction of run-of quarry quartz in grit and powder forms to industrialized countries without further value addition. Therefore, an alternative approach is evaluated and recommended to achieve a higher level of value addition by exporting semi-processed and processed industry specific quartz raw material. Chemical composition of major types of vein quartz and mining activities of 7 vein quartz deposits and mass scale quartz processing at a plant located in Badulla district of Uva Province, Sri Lanka have been subjected to study. Critical step evaluation of the process in mining, transport and processing activities was carried out with reference to critical trace elements by using isodynamic magnetic separator, inductively coupled plasma optical emission spectroscopy and atomic absorption spectrophotometer. Results show that colourless quartz contains the lowest trace elements concentration while feldspar-associated quartz has the highest. Lowest Fe, Al, Cr, Mn and Ni levels were observed in colourless and milky quartz in selected deposits. Manual chipping of Fe stains reduce Fe levels of 300 ppm while soil contamination increase Fe levels by 375 ppm. Transportation in iron lined trailer has a possibility to increase Fe levels up to 150 ppm due to contact with rust layer. In processing, Fe levels can be reduced by more than 20 ppm by removing the finer size fraction in each crushing step. Further reduction can be obtained to a level below 9 ppm by dry magnetic separation with 10,000 gauss 24 trays magnetic separators. Through selective mining and exercising quality control in mining, transportation and processing activities, industry specific quartz raw material can be produced.

Key words: Vein quartz, Chemically reinforced glass, Silica

DEDICATED TO SRI LANKANS WHO CONTRIBUTED FOR FREE EDUCATION

ACKNOWLEDGEMENT

I would firstly like to express my sincere gratitude to my supervisors Prof. N.P. Ratnayake and Dr. L.P.S.Rohitha for the guidance, dedication and helping hand throughout this study and made this research to harvest its maximum benefits.

My deepest gratitude is extended to Mrs. Y.P.S. Siriwardhana, Chief Chemist of Geological Survey and Mines Bureau for the assistance, encouragement and support extended to me at all times during my work as area specialist and guidance in chemical analysis with ICP-OES.

I am also grateful to Mr. K. Kumaranayagam, Chairman of Woolim Lanka Pvt Ltd, all the staff at Woolim Lanka for readily providing all the facilities to successfully carryout this research within fully equipped chemical laboratory for a time period of three years.

I would also like to acknowledge The Head of the Department, research coordinator, academic staff and non-academic staff members of Department of Earth Resources Engineering, for providing me the opportunity and facilities to use laboratories and resources for the research.

My special gratitude to my parents, wife, son and friends for their valuable guidance and support offered during my research period.

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LIST OF ABBREVIATIONS

AAS	-	Atomic Absorption Spectrophotometer
BOI	-	Board of Investment
ESR	-	Electron Spin Resonance
FOB	-	Free On Board
GDP	-	Gross Domestic Product
HC	-	Highland Complex
HPQ	-	High Purity Quartz
ICP-OES	-	Inductively Coupled Plasma Optical Emission Spectroscopy
ILO	-	International Labour Organization
NIST	-	National Institute of Standards and Technology
NIR	-	Near Infrared
SiO_2	-	Silicon Dioxide
SRM	-	Standard Reference Materials
VC	-	Vijayan Complex
WC	-	Wanni Complex
XRT	-	X-ray Transmission

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CHAPTER 01

INTRODUCTION AND OBJECTIVES

1.1. Introduction

This chapter provides a short description of the background and justification of the study area and the research problem.

1.1.1. Background

Silicon dioxide (SiO_2), also known as silica, is the most abundant mineral on earth and commonly found in nature as "quartz". The exceptional physical and chemical properties make it suitable for high-tech modern applications. Applications of high purity quartz in the high-tech industry is numerous. A few of them includes semiconductors, microchips, industrial integrated circuits, high temperature lamp tubing, telecommunication devices, optical fibers, microelectronics, chemically reinforced glasses and solar silicon cells (Huang et al., 2013; Haus et al., 2012). High purity quartz deposits with SiO_2 content over 99% has made them suitable as sources of raw material for high-tech applications or as mass scale products such as value-added glass and refractories. In the value-added glass industry, special optical glasses, hard disk drive glasses and chemically reinforced glass or tempered glass have developed a high demand in the last decade with the rapid increment of the usage of touch screen mobile phones, tablets and computers. With the technological improvements of those devices in recent history, resolution, clarity and durability of glass have to be improved and the selection of quality raw material becomes critical. Most of these products are quite expensive and production of such high-end items can generate a considerable amount of revenue.

Sri Lanka is rich in quartz mineralization with an abundance of major vein quartz deposits in many parts of the island with purity levels over 99.5% of SiO_2 (Nawaratne, 2009**.** These high purity deposits hold great potential for the future development of the country's mineral industry. Non-industrialized countries, including Sri Lanka export raw quartz in grit and powder forms without further value addition to industrialized countries such as Japan, China and South Korea (Mineral Year Book, 2015). Grit and powder production only involves enforced size reduction of the run-of-quarry quartz. Countries like Sri Lanka with low Gross Domestic Product (GDP) are compelled to mobilize its mineral wealth to earn the much-needed foreign exchange. Further processing is carried out in these industrialized countries for the removal of impurities using simple as well as advanced techniques to turn out quartz products suitable for different high-tech applications, earning high revenue.

Sri Lanka is in a position to carryout part value addition, locally. However, the government focus is on developing finished good products instead of exporting mineral products in raw form. Developing high-tech products requires considerable capital investment, expertise and advance processing technology, which are lacking in most of the developing countries. During the last decade, the Sri Lankan mineral sector has recorded a significant growth in exports of crushed quartz at a very low level of value addition.

For instance, high end glass industry requires SiO_2 with Iron (Fe) content less than 20 ppm and Aluminum (Al) with less than 500 ppm (Vitalis et al., 2014). On the other hand, semiconductor industry requires silica with Fe content less than 10 ppm and Al content less than 80 ppm respectively (Vitalis et al., 2014). Point defects are usually present as foreign ions in the lattice or interstitial positions of the silica (Santos et al., 2015; Pathirage et al., 2017). Therefore, their removal by simple techniques is not possible and consequently, the deposits are considered not suitable as sources of quartz for the semiconductor industry. However, most of these deposits contain Fe at levels varying from 10 to 300 ppm in in-situ samples and this level of Fe is mostly due to secondary contamination and Fe bearing accessory minerals rather than replacements in point defects (Santos et al., 2015; Banza et al., 2005; Pathirage et al., 2015).

Quartz has a stable molecular structure of SiO_2 which allows only a small amount of other elements to enter the lattice. However, minute amounts of interstitial impurities can enter as lattice-bound impurities replacing Si^{4+}in the Si–O tetrahedran. According to Flem et al (2002) interstitial impurities that fit into structural channels are mostly small monovalent ions. Jung (1992) identifies that, Al, B, Ge, Fe, H, K, Li, Na, P and Ti as true lattice-bound impurities while Ca, Cr, Cu, Mg, Mn, Pb, Rb and U result from microscopic solid and liquid inclusions.

1.1.2. Research Problem

In the current research, an alternative approach is evaluated to achieve a higher level of value addition aiming at export of semi-processed and processed silica products suitable for specific industrial applications. Chemical composition of major types of vein quartz and mining activities of 7 vein quartz deposits located in the Badulla District of Uva Province of Sri Lanka and mass scale quartz processing at a plant located in Badulla District has been subjected to study. Critical step evaluation of the process in mining, transport and processing activities was carried out with reference to Fe and critical trace elements by using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) and Atomic Absorption Spectrophotometer (AAS). Results show a significant reduction of impurities can be achieved through quality control in mining, transportation and processing.

1.2. Objectives

1.2.1. Research Objectives

- Assessing the chemical composition of major types of vein quartz and identifying the key contaminants in the study area.
- Assessing possibilities of minimizing contamination of quartz due to,
  - Mining
  - Mineral (Quartz) Transportation
  - Processing

CHAPTER 02
LITERATURE REVIEW

2.1. Introduction

This chapter provides a short description of the literature review conducted relating to the research.

2.1.1. Introduction–Silica

Silica is the most abundant oxide in the earth's crust in igneous, metamorphic and sedimentary rocks and occurs both as free silica or combined with other elements and compounds. SiO_2 minerals and rocks have been formed by primary and secondary magmatic, hydrothermal or sedimentary processes or during digenesis and metamorphosis (Heany et al., 1994). Pegmatite or hydrothermal quartz, quartz sands and sandstones, chert, flint and quartzite are the results of these processes, whereas digenesis of organic silica skeletons, e.g. diatoms, radiolaria, siliceous sponges result in the formation of siliceous rocks, e.g. porcellanites, diatomites or radiolarites (Fuchtbauer, 1988).

Due to high abundance and weather resistance, quartz has been used in different applications such as tools, weaponry, jewellery and as traditional building material for centuries. With the passage of time, due to its exceptional physical and chemical properties, quartz has become a widely used raw material for numerous industrial applications such as semiconductor, solar cells and value added glasses (Haus et al., 2012). For this, naturally occurring quartz deposits such as vein quartz, pegmatites etc. are used. Due to the increasing quality requirements, synthetic crystalline quartz and non-crystalline quartz have been developed for certain highly advanced applications (Blankenburg et al., 1994).

Quartz is characterized by specific properties such as crystal shape, colour, luminescence, trace element content and isotropic composition resulted due to specific conditions of formation.

2.1.2. SiO_2 Modifications and Varieties

There are more than 15 modifications of SiO_2 having the same mineral phase with the formula of SiO_2, but a different crystal structure as shown in Table 2.1.2.

Among them, trigonal low-temperature alpha-quartz is the most frequently used in technical applications (Gotze, 2012).

Table 2.1.2: Modifications of SiO_2 having the same mineral phase and their crystal structure

Silica Group	Silica Type	Crystal Structure
Quartz-tridymite-cristobalite group (atmospheric and low pressure)	Low (α)-quartz	Trigonal
	High (β)-quartz	Hexagonal
	Tridymite	Monoclinic
	High-tridymite	Hexagonal
	Cristobalite	Tetragonal
	High-cristobalite	Cubic
	Melanophlogite	Cubic
	Fibrous SiO_2	Orthorhombic
	Moganite	Monoclinic
Keatite-coesite-stishovite group (high and ultra-high pressure)	Keatite	Tetragonal
	Coesite	Monoclinic
	Stishovite	Tetragonal
	Seifertite	Orthorhombic
Lechatelierite-opal group (amorphous phases)	Lechatelierite	Natural silica glass
	Opal	H_2O-bearing, solid SiO_2 gel

Source: after Gotze, 2012

Many chemical and physical properties of quartz and the other silica polymorphs such as trace element content, isotopic composition, and luminescence are determined by their real structure (Blankenburg et al., 1994; Gotze, 2009). These varying properties of quartz result in the existence of several varieties, e.g. mineral phases with the same chemical composition of SiO_2 and the same crystal structure, but different appearance in shape, colour or varying physical properties (shown in Figure. 2.1.2) (Rykart 1995; Blankenburg et al., 1994).

2.2. Characteristics of Quartz

- Chemistry : SiO_2
- Class : Silicates
- Subclass : Tectosilicates
- Group : Quartz

- Color : Most commonly clear (Rock Crystal), but also found in white (Milky or snow Quartz), greys or browns to blacks (Smokey Quartz), along with many other colors of the spectrum. Cryptocrystalline varieties can be multicolored.
- Luster : Glassy to vitreous as crystals; crypotocrystalline forms are usually waxy or dull, but can be vitreous.
- Crystal System : Trigonal ;3.2
- Crystal Habit : Widely variable, but most commonly as hexagonal prisms terminated by two rhombohedrons, which create a six – sided pyramid. Also common are druse (or drusy) forms, which are host rock lined with multiple pyramid crystals of quartz. Massive forms can be of any type.
- Cleavage : Very week in 3 directions - rhombohedral.
- Fracture : Conchoidal
- Hardness : 7 in Moh’s scale
- Specific Gravity : 2.65
- Streak : White
- Other characteristics: Striations on prism faces running up the length of the crystal (perpendicular to C axis), piezoelectric, and refractive index is 1.54 - 1.55.

2.3. Properties of Quartz

Specific properties of quartz determine the quality of the quartz raw material. Under various thermodynamic conditions, point defects, dislocations and micro inclusions can be incorporated into quartz during crystallization and by secondary processes, e.g. alteration, irradiation, diagenesis or metamorphism resulting varying types of quartz (Gotze, 2012).

2.3.1. Silica Content

Silica content (SiO_2 content) is the key indicator of purity level of quartz raw material. Silica with SiO_2 levels of 97% - 99% is used as raw material for plate or sheet glass and ceramic products (Blankenburg et al., 1994). Silica with SiO_2 levels 99.5% - 99.99% is used as raw material for high tech applications such as fillers for semiconductors, optical fibers, quartz glass, chemically reinforced glass and quartz crucible. Natural quartz with SiO_2 levels over 99.99% is rare and directly used as a raw material in high tech applications. Further, processing with chemical and physical techniques, upgrade SiO_2 levels up to 99.999%, commercially known as Lasca, used in ultra-purity quartz industry for the manufacture of quartz glasses for semiconductors and optical lenses (Blankenburg et al., 1994; Muller et al., 2005). In synthetic quartz, SiO_2 levels varying from 99.9992% to 99.9999% is called ultra-high synthetic quartz whereas, SiO_2 levels varying from 99.9999% to 99.99999% with hyper synthetic quartz (Vitalis et al., 2014) is used in silicon cells, zeolites and adsorbents (shown in Figure 2.3.1).

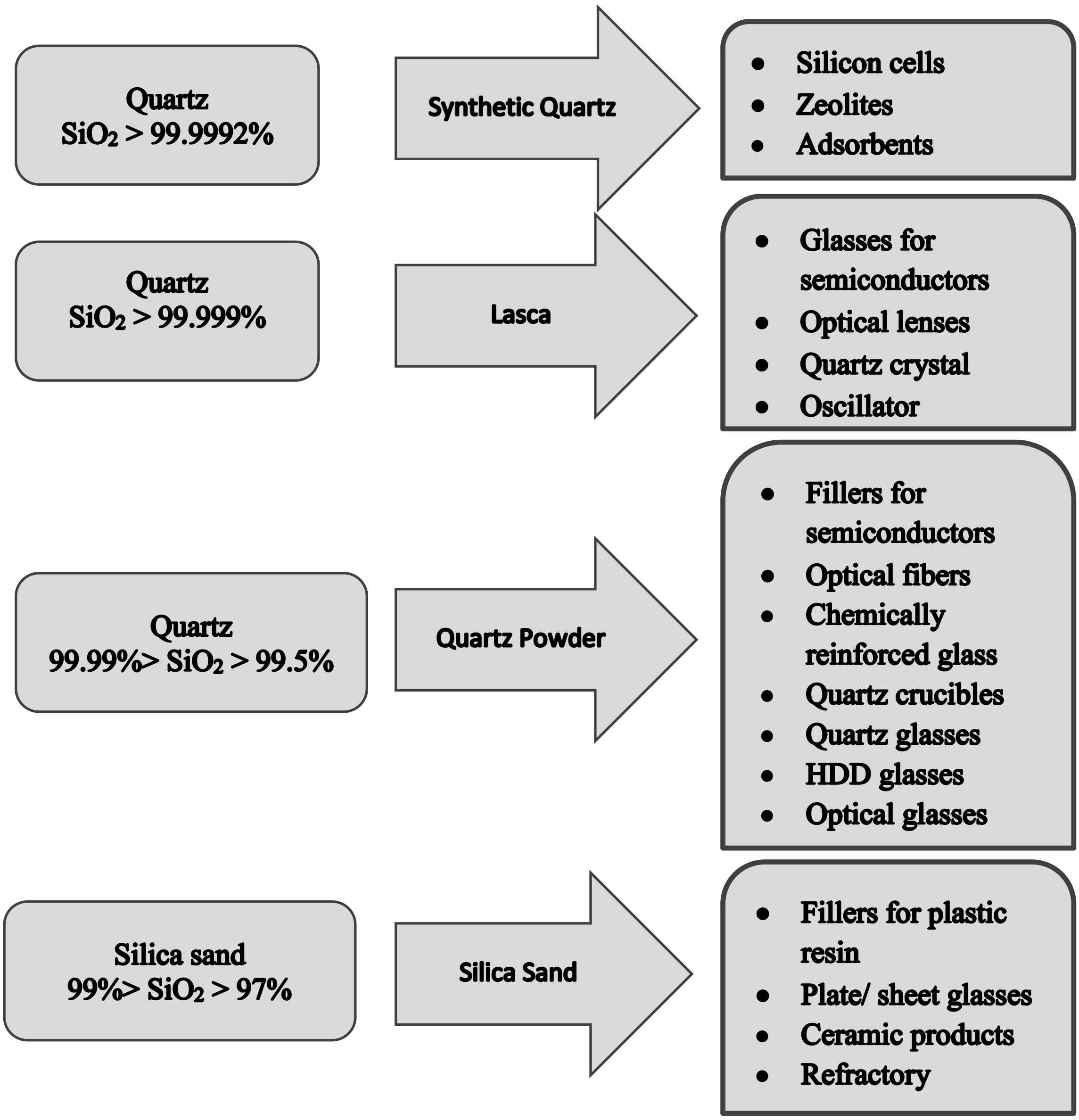


Figure 2.3.1: Purity levels with industrial applications

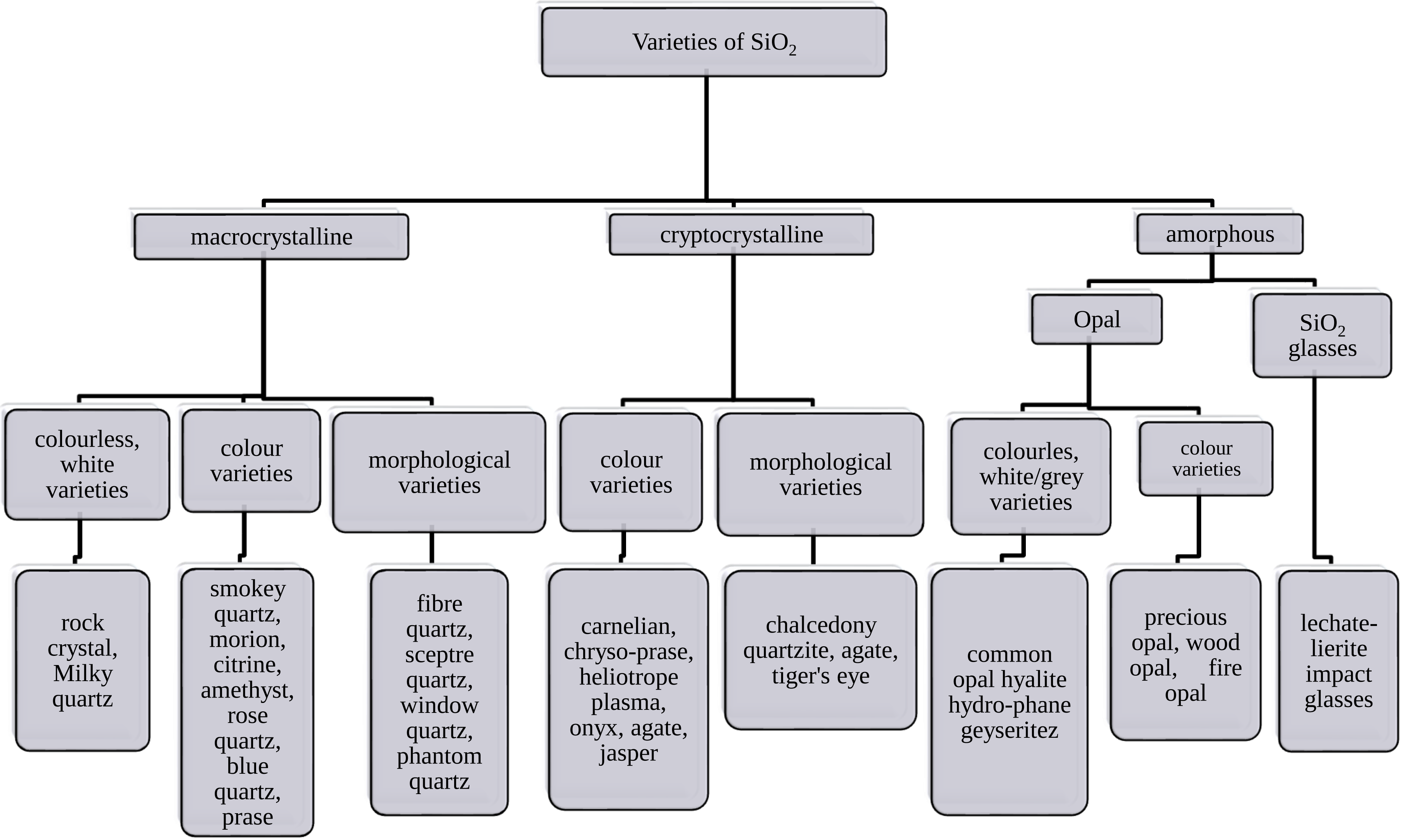


Figure 2.1.2: Varieties of quartz

Source: modified after (Gotze, 2012)

2.3.2. Point Defects

Point defects in quartz are in general extrinsic defects occurring due to the incorporation of foreign ions in the lattice and interstitial positions. Intrinsic defects occur due to the displacement of different types of atoms and/or associations with Silicon or Oxygen vacancies (Kostov and Bershov, 1987; Weil, 1984, 1993). Plotze, (1995), Stevens-Kalceff et al (2000), Stevens-Kalceff, (2009) and Pan et al (2009) have identified more than twenty different types of point defects using techniques such as Electron Spin Resonance (ESR), Luminescence Spectroscopy and absorption measurements. .

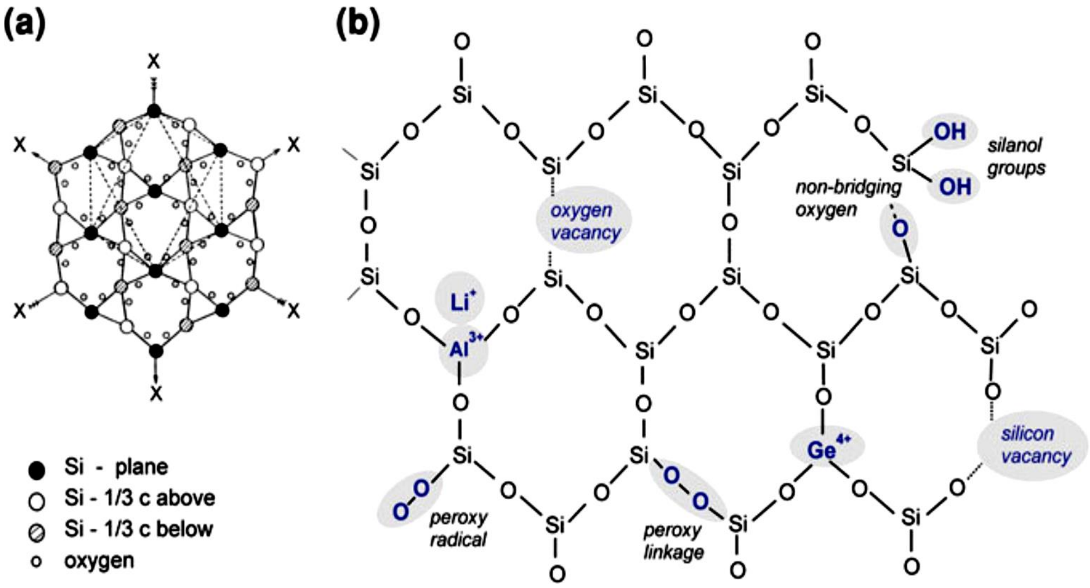


Figure: 2.3.2 Schematic structure of α-quartz: (a) modified after (Beall, 1994) and most common point defects: (b) modified after (Gotze, 2009)

The most common trace-element related defect centre in quartz is the [AlO$_4$]^{0}centre caused by substitution of Si^{4+} by Al^{3+} with an electron hole at one of the four nearest O^{2-}ions (Griffiths et al., 1954). The precursor state for this paramagnetic centre is the diamagnetic [AlO$_4$/M$^+$]^0 centre with an adjacent charge compensating a cation (M$^+$ = H$^+$, Li$^+$, Na$^+$) in interstitial position. According to O'Brien, (1955) and Cohen, (1956) smokey quartz forms as a result of the conversion of [AlO$_4$/M$^+$]^0 centre into the optically active [AlO$_4$]^{0}centre by gamma irradiation or, X-rays. Fe, Ge and Ti are other common substitutional trace-element centres associated with quartz (Mackey, 1963; Mineeva et al., 1991; Plotze, 1995). Further, several point defects can be attributed to oxygen and silicon vacancies or oxygen excess (Griscom, 1985; Nishikawa et al. 1994).

The analysis of point defects is essential to enable the use of quartz in several highly-advanced technical applications. Point defects strongly affect the structural, electrical and optical properties of quartz and resulting in electrical instabilities in SiO_2 insulator layers (Blankenburget al. 1994).

2.3.3. Trace Elements

High purity levels of quartz found in the earth crust is due to the fact that only a few ions can substitute Si^{4+} in crystal lattice. Therefore, most trace element concentrations in quartz remain below 1 ppm (Muller et al., 2002). The structural incorporation of Al^{3+}, Ga^{3+}, Fe^{3+}, Ge^{4+}, Ti^{4+} and P^{5+} in the regular Si^{4+} lattice has been proven by Weil (1984, 1993). Al is found to be the most frequent substitute due to its common occurrence and similar ionic radius of Si^{4+}. Fe and Ti substituting Si are bound on mineral micro inclusions such as rutile or iron oxides. Other cations such as H^+, Li^+, Na^+, K^+, Cu^+ and Ag^+ enter the lattice as charge compensating ions and Na and K are hosted by fluid inclusions (Bambauer, 1961; Perny et al., 1992; Gotze et al., 2004; Miyoshi et al., 2005; Jourdan, 2008; Muller and Koch-Muller, 2009; Lehmann et al., 2009).

For the identification of conditions of mineral formation, trace elements play an important role as indicators. Greatest potential for high purity quartz raw material is found in pegmatite quartz, metamorphogenically mobilized quartz veins and some hydrothermal quartz. According to Blankenburg et al., (1994) correlating impurity concentrations and the formation temperature of host quartz lead to establish that the lowest trace element concentration can be expected in the temperature range between 480^0C and 530^0C.

To work out the processing strategy of quartz and their application in the industry, knowledge on trace element content in quartz and mechanisms of incorporation is important. The concentration limits of certain trace elements in SiO_2 raw material for high-tech applications are very low (refer Table 4.2-7); for instance, the production of lamp tubing and optics requires high-purity materials with Al concentrations below 20 ppm. Quartz with Al impurity level below 20 ppm is required for manufacture of semiconductor based materials and crucibles whereas, micro-electronic devices need quartz with impurity level of Al below 10 ppm and U and Th concentrations below 2 ppb. The production of solar silicon needs raw materials with P and B levels below 0.1 ppm and 0.08 ppm concentrations respectively (IOTA, 2017).

2.3.4. Fluid and Mineral Inclusions

Mineral and fluid inclusions can significantly influence the trace-element composition of quartz. Residues of mineralizing fluids and paragenetic minerals can be present during formation of the quartz mineral. Furthermore, micro inclusions forming during ex-solution processes after crystallization provide information about formation paragenesis, temperature of formation, chemistry of mineralizing fluids, etc. (Van den Kerkhof and Hein, 2001). Type and amount of fluid inclusions in quartz raw material can influence the melting behavior of SiO_2 raw materials in industrial applications (Gemeinert et al., 1992). In the glass industry, the melting behavior is affected by the presence of trace refractory minerals such as zircon, aluminium silicates (Parks, 1984).

2.4. Upgrading Quartz Using Processing Techniques

Based on the geological conditions of the quartz deposit and required quality standards, processing stages have to be designed to manufacture quartz raw material. Currently, diverse methods of advance size reduction (comminution) technology are available to convert raw quartz in to high purity quartz products. Liberation of mineral impurities takes place during the reduction process of raw quartz by means of comminution. Further mechanical, physical, chemical and thermal steps are used to separate or dissolve the impurities to meet the final quality requirements in the finished products.

Generally, quartz mineral is processed using the key processing steps such as pre-processing, physical processing, chemical leaching and thermal treatment. However, in advanced processing, magnetic separation, high tension separation, acid washing, chemical leaching, hot chlorination, calcination and flotation play a major role.

The main stages of upgrading are summarized as follows,

- Pre-processing
- Physical processing
- Chemical leaching
- Thermal treatment

2.4.1. Pre-processing

Pre-processing is an essential processing stage in quartz processing and, this stage is required to liberate mineral impurities and fluid inclusions. In pre-processing sizing, visual sorting, optical mechanical sorting, chipping, classification to product particle size and electrodynamic fragmentation take place.

2.4.1.1. Initial sizing

Mostly, vein quartz mining operations are surface operations conducted with human labour, backhoe or bulldozer primarily to remove the overburden of quartz veins. Once the vein is exposed, it is further cleaned with backhoe and subjected to drilling and blasting. ANFO and water gel explosives are used for blasting to obtain sized quartz boulders. Careful blasting is necessary to prevent over fragmentation which may result in excessive losses and ore dilution. The resulting boulders are resized to 6×6 inch lumps by mechanical means and manual labour.

2.4.1.2. Visual sorting

Quartz lumps are visually sorted in to different colour varieties such as rose, smokey, colourless and milky quartz selecting required types based on the quality requirements of the end product.

2.4.1.3. Optical mechanical sorting

With technological developments, highly accurate and effective optical sorting devices have been designed and currently used in the industry. Optical sorting separates the raw materials on the basis of differing colour and shape, and may improve, or even replace, costly selective mining or hand sorting practices. For grain detection, fully automated sensor-based sorting devices equipped with color CCD-cameras, X-ray Transmission (XRT) and Near Infrared (NIR) technology are used. After detection in the bulk flow, non-specified grains are selectively extracted by a precise pulse of pressurized air from a high performance nozzle system. This method is more effective in sorting for size fractions below 40 mm, where manual sorting is not economical. In practice, differently coloured quartz fractions present as rose quartz are separated by optical sorting and smoky quartz with radiation induced discolorations. Further, clear quartz can be separated from milky quartz based on the amount of fluid inclusions present.

2.4.1.4. Chipping

Manual chipping is used to separate differently coloured quartz fractions such as patches of Iron (Fe) stains incorporated in crystal boundaries due to ground water and other secondary contaminations (Dal Martello et al. 2011a, b). General practice in the industry is manual chipping out of contaminant parts by visual observation.

2.4.1.5. Comminution

Surface contaminations in mined quartz lumps need to be removed by washing and cleaning before subjected to comminution to produce grit and powder size particles. Crushing and grinding process should be geared to selectively liberate mineral inclusions and reduce wear related contamination, specially secondary Fe contamination (Andres et al., 1999).

2.4.1.5.1. Mechanical comminution

Currently, Sri Lankan quartz processors use jaw, cone and roller crushers for size reduction leading to liberation of mineral impurities. However, the mechanical comminution processes contaminate high quality quartz grit and powder by adding wear related particles in to the mix. According to Pathirage et al., (2015), wear related particles accumulate in the finer product fraction. Therefore, in high-purity quartz industry, alternative comminution techniques are used.

2.4.1.5.2. Autogenous grinding

In autogenous grinding, a widely used method of comminution, quartz is ground on a high purity quartz bed and contamination from the autogenous grinding internal surfaces mill wear is minimized.

2.4.1.5.3. Electro-dynamic fragmentation

Electro-dynamic fragmentation is used in high purity quartz processing to liberate impurities and minimize under size particles contamination as well. In Electro-dynamic fragmentation, a high voltage discharge generates shock waves which fracture quartz lumps along the crystal boundaries. Since most mineral impurities are associated in crystal boundaries, liberation process is more efficient than mechanical comminution techniques (Dal Martello et al., 2011b). Further, a significant increase in yield occurs compared with that of mechanical comminution techniques. Therefore, electrodynamic fragmentation is much favored in high purity quartz processing.

2.4.2. Physical Processing

Differing responses of quartz to physical processes such as attrition, magnetic separation, high tension separation and flotation enable separation of impurities during the processing stage.

2.4.2.1. Attrition

Quartz particle surfaces are cleaned in the attrition process where fine particles such as clay minerals or iron oxide coatings attached to quartz surfaces are either washed away or liberated to be followed by subsequent physical separation.

2.4.2.2. Magnetic separation

Heavy minerals attached to quartz particles are either paramagnetic or ferromagnetic. Therefore, magnetic separation technique can be effectively used to remove minerals with those characteristic by trapping them in a magnetic field. Ferromagnetic minerals such as Fe^{3+}, Ni and Co requires a low magnetic field strength than paramagnetic minerals to separate from quartz (Haus et al., 2012). Therefore, magnetic fields with different strengths can be applied for the removal of paramagnetic or ferromagnetic minerals.

2.4.2.3. High tension separation

Due to differences of surface conductance of minerals, high tension techniques are used to separate them. Uniform flow of crushed quartz particles is passed through the electrostatic field to separate minerals owing to the differences in surface conductance. In high tension separation, electrodes of the electrostatic separator are placed in a heated chamber and an electrostatic field up to 120 kV is recommended to be applied (Haus et al., 2012). Before feeding, quartz material is activated by either heating or by adding diluted acids. Typically, high tension separation technique is applied to remove feldspar from feldspar-associated quartz (Haus et al., 2012).

2.4.2.4. Flotation

Froth flotation technique is used to separate minerals based on their ability to be wetted, enhanced or suppressed by conditioning reagents. Specially designed flotation tanks are used to separate mineral impurities in quartz and separation takes place in a water-filled medium. Quartz powder is fed to form a suspension which is agitated to avoid sedimentation processes. In the process, a frothing agent is added and air introduced to form rising air bubbles. Hydrophobic particles such as heavy minerals, feldspar or mica attached to air bubbles rise to the surface by forming the froth whereas hydrophilic particles remain at the bottom below the froth layer in the suspension (Haus et al., 2012). The mineral carrying froth is removed. Design of flotation process for quartz is complex and depends on the type of quartz, impurity concentration of selected quartz reserve, degree of liberation and the desired purity of the end product.

2.4.3. Chemical Treatment

Chemical treatment consists of acid washing, leaching and hot chlorination process used to achieve high purity quartz with removal of surface impurities in addition to physical separation methods. Less destructive acids such as hydrochloric, nitric or sulphuric acid etc. are used for acid washing to further liberate surface impurities and leaching techniques with hydrofluoric acid are used to remove liberated surface impurities. Leaching efficiency can be enhanced by heating the solution. Impurities enriched in micro fissures can be removed more effectively by leaching than by physical separation techniques. In the hot chlorination process, quartz is heated up to 1,000–1,200^{0}C in a chlorine or hydrogen chloride gas atmosphere to remove alkali metal impurities associated in quartz (Haus et al., 2012).

2.4.4. Thermal Treatment

Calcination is a commonly used thermal treatment technique to remove fluid inclusions in quartz. In the production of chemically reinforced glass or tempered glass, a significant reduction of air bubbles has been observed due to calcination process with varying pressure and temperature (Gemeinert et al., 1992).

2.5. Sri Lankan Geology

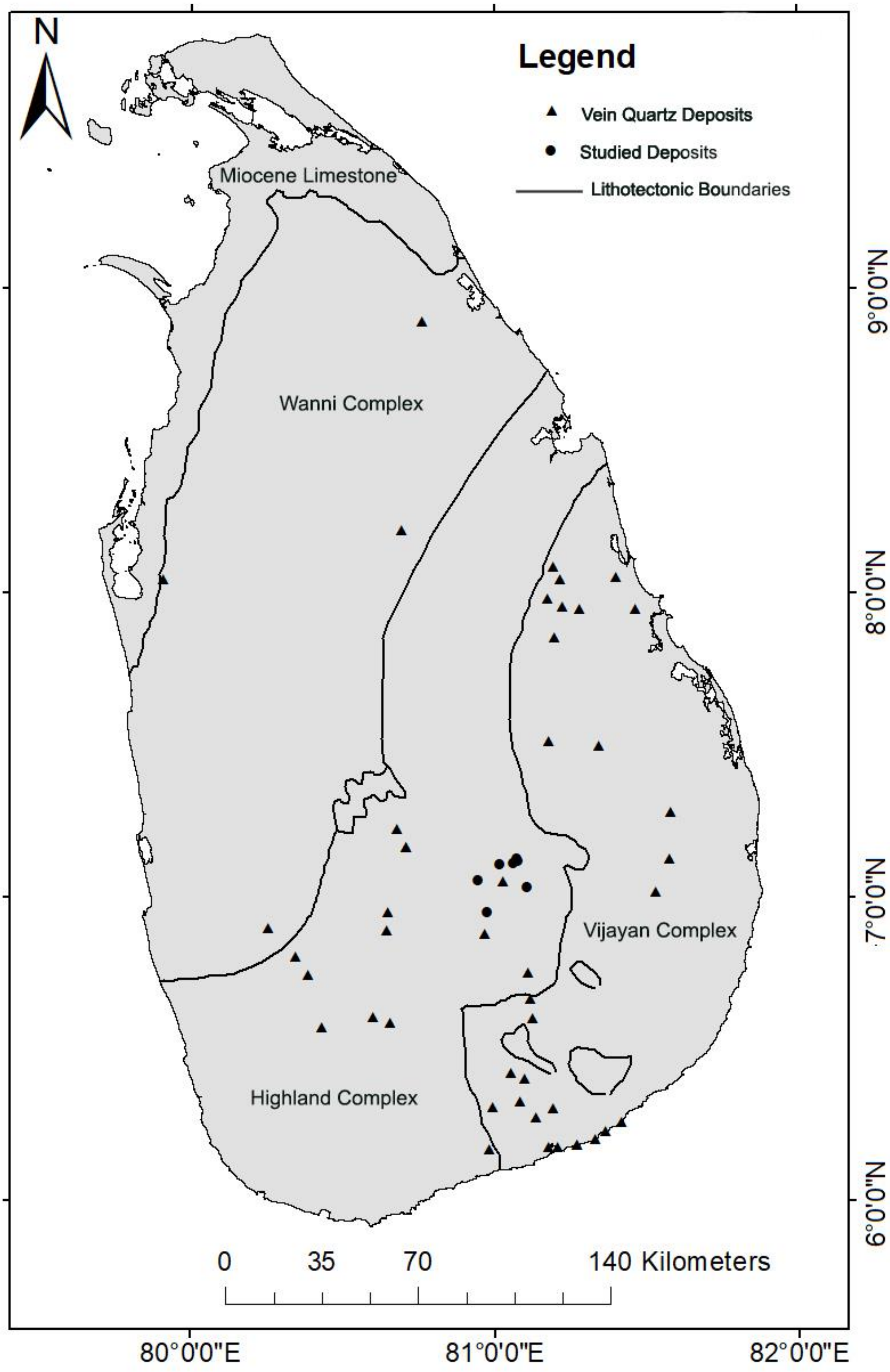
In Sri Lanka, 90% of the island covered by crystalline metamorphic rocks belonging to Precambrian era occurs in three major lithotechtonic units; Highland Complex (HC), Vijayan Complex (VC) and Wanni Complex (WC), (Cooray, 1994) and the rest, 10% is underlain by sedimentary rocks mainly from Jurassic and Miocene era (Figure 2.5.1). HC rocks are metamorphosed to granulite facies and both VC and WC rocks are metamorphosed to upper amphibolite facies. HC rocks are mainly granulite grade khondalite-bearing metasediments, migmatites and granitoid gneisses and charnockites, whereas WC and VC rocks are orthogneisses and migmatites of amphibolite facies complexes (Cooray, 1978; Vitanage, 1985). Patches of arrested charnockites occur mainly in the HC more towards the southwestern part of the island. In the plate tectonic model introduced by Munasinghe and Dissanayake (1982) on the formation of Sri Lankan rock sequences of granulite grade, the boundary between the HC and the VC has been interpreted as a mineralized belt.

2.5.1. Silica Types in Sri Lanka

Silica occurs as vein quartz, silica sand and quartzite in Sri Lankan terrain.

2.5.1.1. Vein quartz

Vein quartz deposits of extreme purity over 99.98% are found in many parts of the island (refer Figure 2.5.1), mainly confined to the central highlands along lithotechtonic boundaries. High purity vein quartz deposits occur in Balangoda, Rattota, Wallawaya, Badulla and Galaha (Herath, 1995; Nawaratne, 2009). Vein quartz normally occurs on the surface as very large boulders and may in some places spread over an area of a few hectares. Some deposits may extend to the depth. After 1990, large quantities of vein quartz has been exported and the export demand has rapidly grown due mainly to high purity of the Sri Lankan quartz (Herath, 1995).


N
Legend
▲ Vein Quartz Deposits
● Studied Deposits
Lithotectonic Boundaries
Miocene Limestone
Wanni Complex
Vijayan Complex
Highland Complex
0
35
70
140 Kilometers
9°0'0"N
8°0'0"N
7°0'0"N
6°0'0"N
80°0'0"E
81°0'0"E
82°0'0"E

2.5.1.2. Silica sand

Deposits of silica sand are widespread in the island and the best-known deposits occur in the Marawila-Nattandiya and Madampe areas. A large deposit of silica sand also occurs in the Ampan-Vallipuram area. Three deposits have been recognized in the Madampe – Nattandiya area. The length of the combined deposits, stretching for 8 to 10 km, greatly exceed the width in places of more than a few hundred meters. The total area covered by silica sand deposits has been estimated at approximately 1000 hectares (Vitanage, 1985).

2.5.1.3. Quartzite

Quartzites are very common in the island and they occur mainly in the HC areas. Pure quartzites are generally coarse or granular, with no foliation or bedding visible. In feldspathic quartzite, kaolinised feldspar is present which is often stained and give the whole surface of the rock a brownish appearance. Quartzites are not utilized for any local industry in the island, although the pure varieties may be considered for use in ceramics and allied industries. High quality quartzites suitable for industry occur in the Balangoda area. Chert which is a finely crystalline siliceous material occurs at various points in the island. It could be used as an ornamental stone. Chert deposits are common in the Ambalangoda area (Herath, 1995).

2.6. Quartz Production and Export

Demand for vein quartz as a raw material for high tech applications has increased rapidly over the last three decades and subsequently utilization of Sri Lankan natural high purity quartz deposits has also increased. With the requirement of high quality raw materials for high tech product in the world market, several quartz processing companies have been started in Sri Lanka (eg : Krishna Mines, Cey Quartz MBI, Alchemi Bolders, Ceylon Quartz Industries, Blue Bay Mines, Woolim Lanka, etc). Currently, Sri Lanka exports around 30,000 mt per year contributing to the much needed foreign revenue to the country.

Table 2.6: Production quantities of vein quartz

Year	2009	2010	2011	2012	2013	2014
Quantity (tons)	30409	34437	34903	32320	36478	33712
Value (Rs) (million)	705.39	1020.58	1119.13	1036.72	1170.00	1081.50

Source: Mineral Year Book 2015, GSMB

Processing of vein quartz to produce micronized powder and grit for export is carried out by the above companies in Sri Lanka. Much of the annual vein quartz production is exported and about 5% has been used in the local ceramic industry. The export of vein quartz in lump form has been stopped since 2010 to promote value addition, locally. Value addition beyond mechanized powdering is encouraged.

Table 2.6-1: Export quantities and local usage of vein quartz

Quantity (mt)	Year				
	2009	2010	2011	2012	2013
Production of Vein Quartz	30,409	34,437	34,903	32,320	36,478
Export Quantity	26,866	31,921	33,354	30,704	31,138
Export Quantity %	88.35	92.69	95.56	95.00	85.36
Local Usage Quantity	3,543	2,516	1,549	1,616	5,340
Local Usage % (Ceramic)	11.65	7.31	4.44	5.00	14.64

Source: Mineral Year Book 2014, GSMB

2.6.1. Export Quantities of Vein Quartz

Sri Lankan quartz is exported to eleven countries (Table 2.6.1), mainly to Japan, Singapore and South Korea. Around 45% of quartz is exported Japan mainly for end user manufacturing and around 25% to Singapore for international trading companies.

Table 2.6.1: Country-wise export quantities of vein quartz

Export Country	**Export Quantities (mt)**							
	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Malaysia	400	680	280	340	980	1280	1000	980
Singapore	6,140	9,460	9,184	10,292	7,977	7766	7812	7812
China	108		110	266	21	1920	20	0
Germany	281			40	45	320	460	567
Israel							1455	2137
Japan	9,056	13,860	16,669	12,526	15,455	15420	14122	15379
Korea	10,838	7,920	7,111	7,220	6,660	7000	4800	4993
Vietnam								125
Australia								163
Taiwan		1		20		10		
India	43							
Total	**26866**	**31921**	**33354**	**30704**	**31138**	**33716**	**29669**	**32156**

Source: Mineral Year Book 2015, GSMB and Draft Mineral Year Book 2016

2.6.2. Export Prices of Vein Quartz

According to Table 2.6.2, vein quartz exports to Japan earns the highest revenue to the country, whereas export to South Korea is lesser. More than 20% of Sri Lankan exports are valued less than USD 210 per mt which is a low price compared to the world market prices. Exports to trading companies in Singapore result in more foreign revenue than direct exports to some of the industrialized countries such as South Korea and Germany who produces end products.

Table 2.6.2: Export quantities and prices of vein quartz

Export Country	**2015**			**2016**		
	Quantity (mt)	**Price ($) per (mt)**	**%**	**Quantity (mt)**	**Price ($) mt**	**%**
Malaysia	1000	305-312	3.37	980	305-309	3.05
Singapore	7812	314-387.9	26.33	7812	306.5-391.5	24.29
China	20	300	0.07	0		
Germany	460	191	1.55	567	201-205	1.76
Israel	1455	180-208	4.90	2137	203-208	6.65
Japan	14122	145-382	47.60	15379	191-499.8	47.83
Korea	4800	165-195	16.18	4993	195-205	15.53
Vietnam				125	250	0.39
Australia				163	200-241	0.51
Total	**29,669**			**32,156**		

Source: Draft Mineral Year Book 2016, GSMB

2.6.3. Sri Lankan Export Taxes Applicable to Vein Quartz

Sri Lankan taxes on export of vein quartz have been revised and export in raw form was prohibited in 2010 to promote local value addition. Currently, the royalty tax of 7% on Free On Board (FOB) price levied goes to the government and exports earning below USD 300 per mt are liable to pay additional cess tax. Cess tax also depends on FOB price. Geological Survey and Mines Bureau collects all the taxes on behalf of the government.

2.6.4. World Market Prices of Vein Quartz

Though Sri Lankan prices are mainly based on size fractionation, world market pricing is based not only on particle size but also on the quality of the quartz product.

Table 2.6.4: Typical silica sand and quartz specification by market

Types of application	SiO_2 Minimum (%)	Other elements (Maximum %)	Typical price ($/mt)
Clear glass grade sand	99.5	0.5	100
Semiconductor filter, LCD and optical glass	99.8	0.2	250
Low grade "high purity quartz"	99.95	0.05	350
Medium grade "high purity quartz"	99.99	0.01	600
High grade "high purity quartz"	99.997	0.003	>5000

Source: Modified after Richard Flook and Vitalis et al., 2015

Note 1: Specific other elements may be limited by application, e.g. Fe_2O_3<100 ppm for float gases and <40 ppm for low iron gloat gases.

Note 2: Generally, "high purity" quartz has Fe_2O_3<15 ppm, Al_2O_3<300 ppm and alkali earth oxides <150 ppm.

Note 3: In some applications, Al_2O_3 can substitute for some SiO_2 e.g up to 1.5%Al_2O_3 in float glass.

Note 4: Limits can vary according to the composition of other raw materials in the application.

2.7. Health Hazard in Quartz Industry

Pneumoconiosis is one of the respiratory occupational diseases commonly encountered in quartz industry all over the world.

2.7.1. Silicosis

Silicosis is a type of pneumoconiosis caused by the inhalation of fine silica dust causing inflammation and scarring the lung tissue. It is one type of Pneumoconiosis in general that can result in from inhaled silica, asbestos, coal, beryllium and other reparable dusts (Martin, 2005). This occurs by inhalation of crystalline silicon dioxide and is one of the serious occupational disease worldwide. (Greenburg, 2007) Although preventive measures are taken, it still remains one of the major repairable occupational diseases. The disorder occurs everywhere, but is especially prevalent in countries with lower and middle income, where it is often under-reported because of poor surveillance.

About 600,000 workers in the UK and more than 3 million workers in Europe have been exposed to crystalline silica from 1990 to 1993. Mostly, less than 100 cases have been reported every year in the UK between 1996 and 2009, and, deaths from silicosis have declined from 28 in 1993, to 10 in 2008 (Health & Safety Executives, 2011). In the USA, more than 121,000 workers have been exposed to concentrations of respirable crystalline silica of 0.05 mg/m^3 or more in 1993 (Linch et.al, 1995) and 3600–7300 silicosis cases occurred annually from 1987 to 1996 (Rosenman ,2003). However, silicosis deaths in young adults (aged 15–44 years), probably are due to intense and recent exposures have not fallen since 1995. China reports the most patients with silicosis, with more than 500,000 cases recorded between 1991 and 1995, and 6000 new cases and more than 24,000 deaths reported annually (WHO Silicosis, 2000). The problem is particularly acute for workers in small-scale mines, who often have an accelerated form of disease. The prevalence of silicosis has greatly declined in recent decades because of effective industrial hygienic measures taken in developed countries. But the disease still prevails to a considerable degree in developing or less developed countries with a lot of mines where mining is a major industry (Martin, 2005).

2.7.1.1. Occurrence of Silicosis in Sri Lankan Quartz Industry

A case study conducted by Siribaddana et al., (2013) in a quartz processing plant in the Central province, Sri Lanka reveals that 5.6% of workers in the processing plant full fill the International Labour Organization (ILO) criteria for diagnosis of silicosis and 93% of the affected workers have been exposed to quartz dust during a period less than 10 year and fit into the category of accelerated silicosis. 85% of the affected workers are found to be below the age of 30 years.

In Sri Lanka, five main quartz processing companies have started operations during the last 18 years. Government enforced size reduction of run-of-the-mine quartz only after 2010. As a result, the probability of incidents of silicosis increased due to dust generation mainly in comminution process. As mitigatory measures, proper dust suppression systems have been put in place. Further, periodical inspections are carried by the government authorities to monitor the compliance levels with visits to processing plants.

Since silicosis is a progressive disease and prevention of dust inhalation is the only effective measure that can be taken to control it among the quartz mining community. In this respect, creating awareness of the health hazard among the workers and management is extremely important in prevention. Dust suppression at the source is the first line of defense while using personal protective equipment is the last barrier. It is the management responsibility to remove the afflicted worker with silicosis from the particular work environment with immediate effect.

CHAPTER 03
MATERIALS AND METHODOLOGY

3.1. Introduction

This chapter provides a broad description of the materials used for the research and a description on the method followed to achieve the objectives.

3.2. Study Area

Chemical composition of major types of vein quartz and mining activities of seven vein quartz deposits located in the Badulla District of Uva Province of Sri Lanka and mass scale quartz processing at a plant located in Badulla District has been subjected to the study. Existing mining, transportation and mineral processing practices were evaluated with detailed analysis carried out at critical steps of the process.

3.2.1. Location

The study area is located in the Badulla District of Sri Lanka (Figure 3.2.1) and the selected seven mines are located along the boundary of Highland and Vijayan complexes. Quartz processing factory is in the vicinity of Karamatiya, Meegahakiula, Adaulpotha and Kandakatiya villages with the longitude and latitude being 81^{0}01’59.09”E and 7^{0}11’54.13” N and the total area covered by the factory premises is 5 Acres (Figure 3.2.1-1).

Table 3.2.1: Description of Sample Locations

Site	**Village**	**Long**	**Lat**	**Quartz Types Presented in Sites**
Q1	Komarika	81^{0}06’	7^{0}12’	Milky, Transparent
Q2	Lunugala	81^{0}05’	7^{0}11’	Milky, Rose
Q3	Katakella	81^{0}10’	7^{0}03’	Milky, Transparent, Rose, Smoky, Mica Associated
Q4	Maliyadda	81^{0}00’	7^{0}10’	Milky, Transparent, Smoky, Feldspar Associated
Q5	Komarika	81^{0}07’	7^{0}11’	Milky, Rose, Mica Associated
Q6	Galauda	80^{0}87’	7^{0}06’	Rose, Smoky, Feldspar Associated
Q7	Haliela	80^{0}96’	6^{0}93’	Smoky, Mica Associated, Felspar Associated

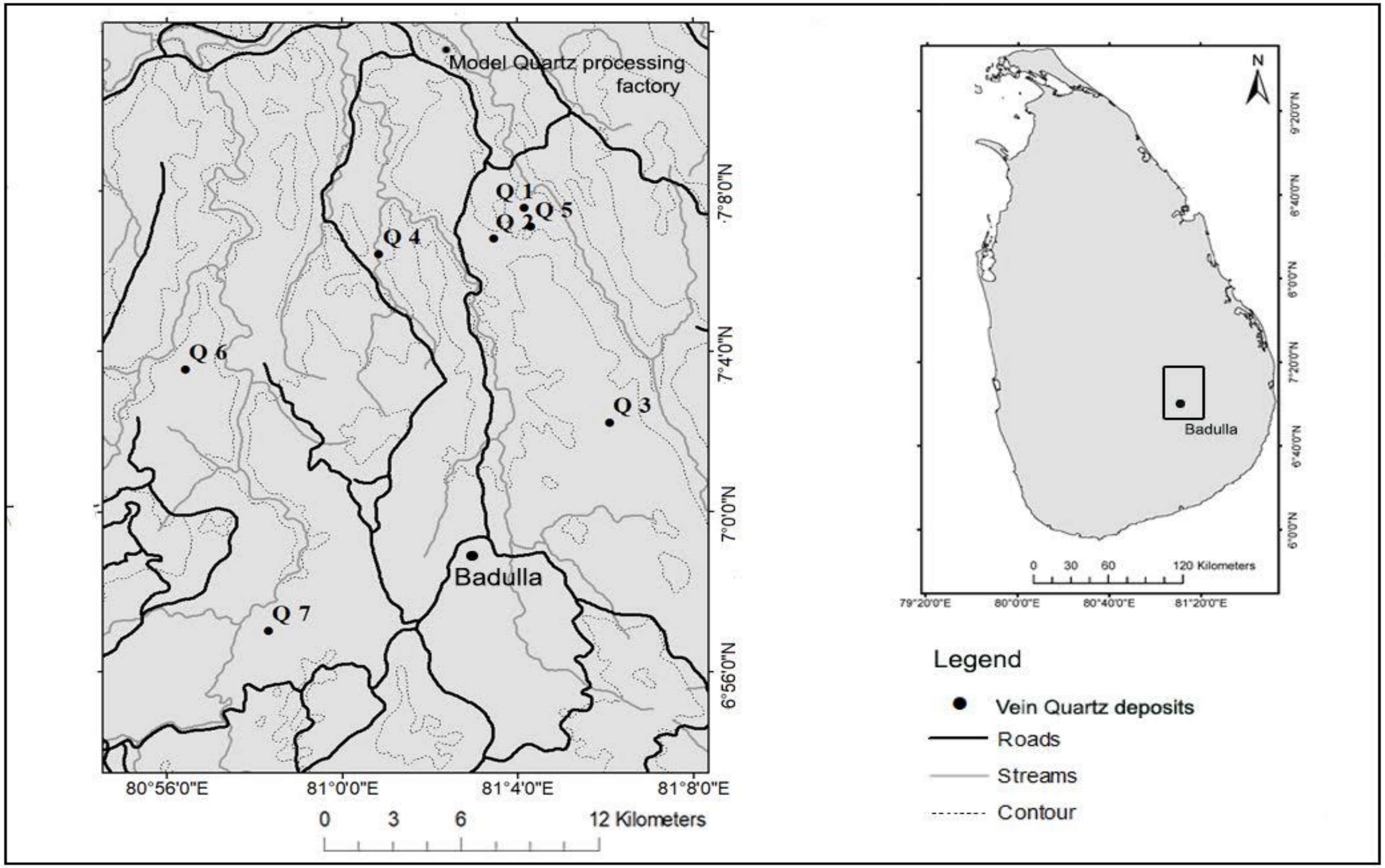


Figure 3.2.1: Location of seven quartz deposits, Badulla, Sri Lanka

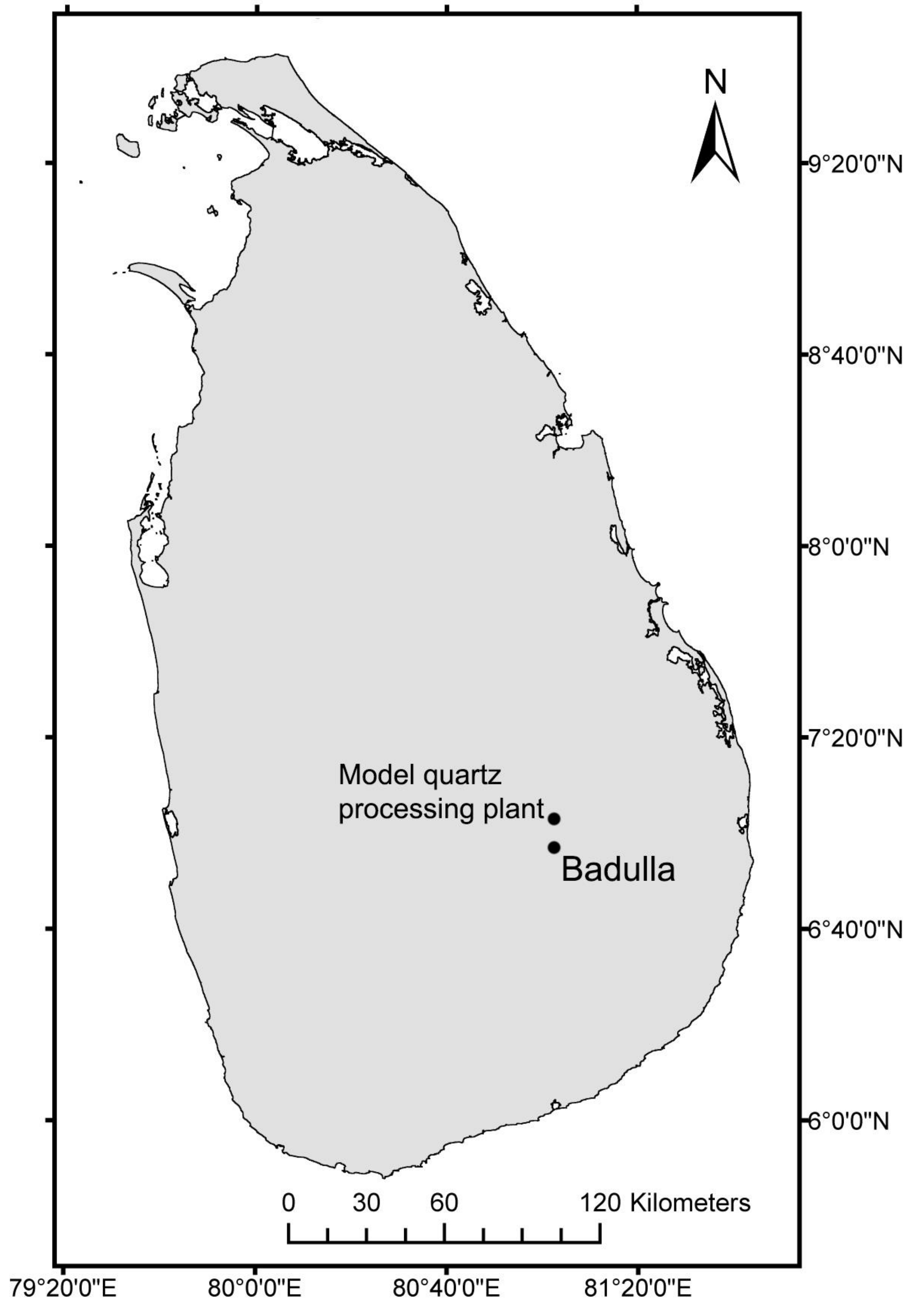


Figure 3.2.1-1: Location of the quartz processing factory, Badulla, Sri Lanka

3.2.2. Climate

The area receives an annual rainfall below 1250 mm, from the North-East monsoon during December to February and South West monsoon during May to September. In addition, there are minor convectional rains during inter monsoon periods. Badulla area receives a low annual rainfall compared to other areas in the country. Figure 3.2.2 shows the monthly average rainfall in the Badulla area from 1994 to 2014.

Figure 3.2.2 clearly shows that the two monsoons and North-east monsoon is dominant in the study area. Except April, extending from January to September rainfall is less than 50 mm. A relatively high rainfall is received during the wet season from October to December.

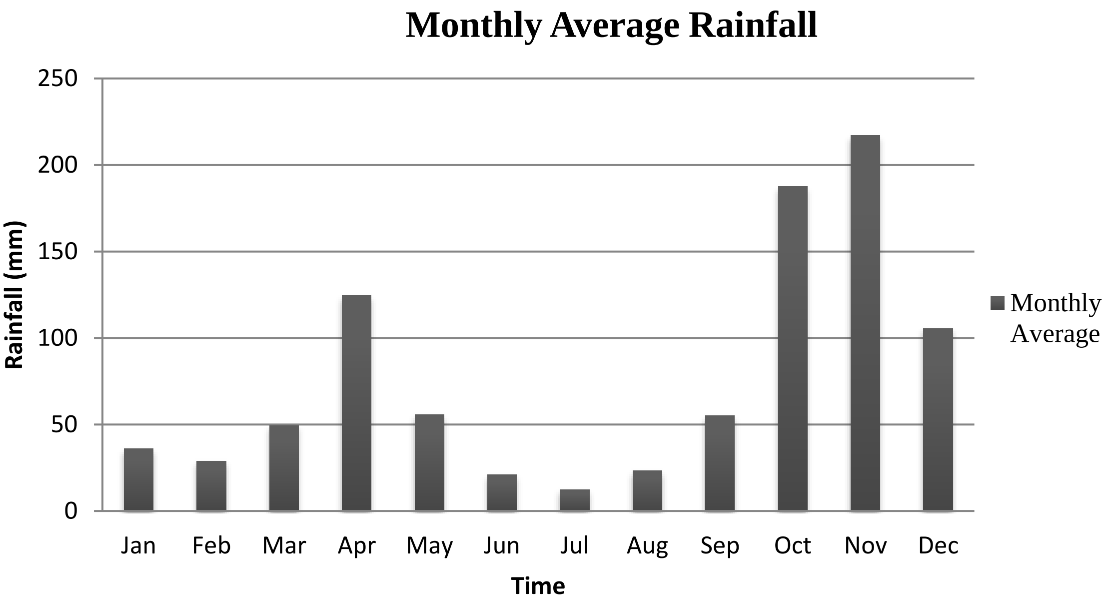


Figure 3.2.2: Monthly average rainfall in Badulla area from 1994 to 2014

3.3. Methodology

3.3.1. Selection of Sample Location

In this study, seven sample locations were considered,

3.3.1.1. Quartz processing plant

The model processing plant was established in 2009 as an export oriented venture obtaining the approval of the Board of Investment (BOI) of Sri Lanka. It is equipped with state of art technology and the production capacity of the factory is 2,000 – 3,000 mt per month with wealth of experience gathered over a period of five years in exploration and mining of quartz. Commercial operations of the company commenced in May 2012. The direct workforce of the company is 50 employees. Existing quartz processing flow chart is shown in Figure 3.3.1.

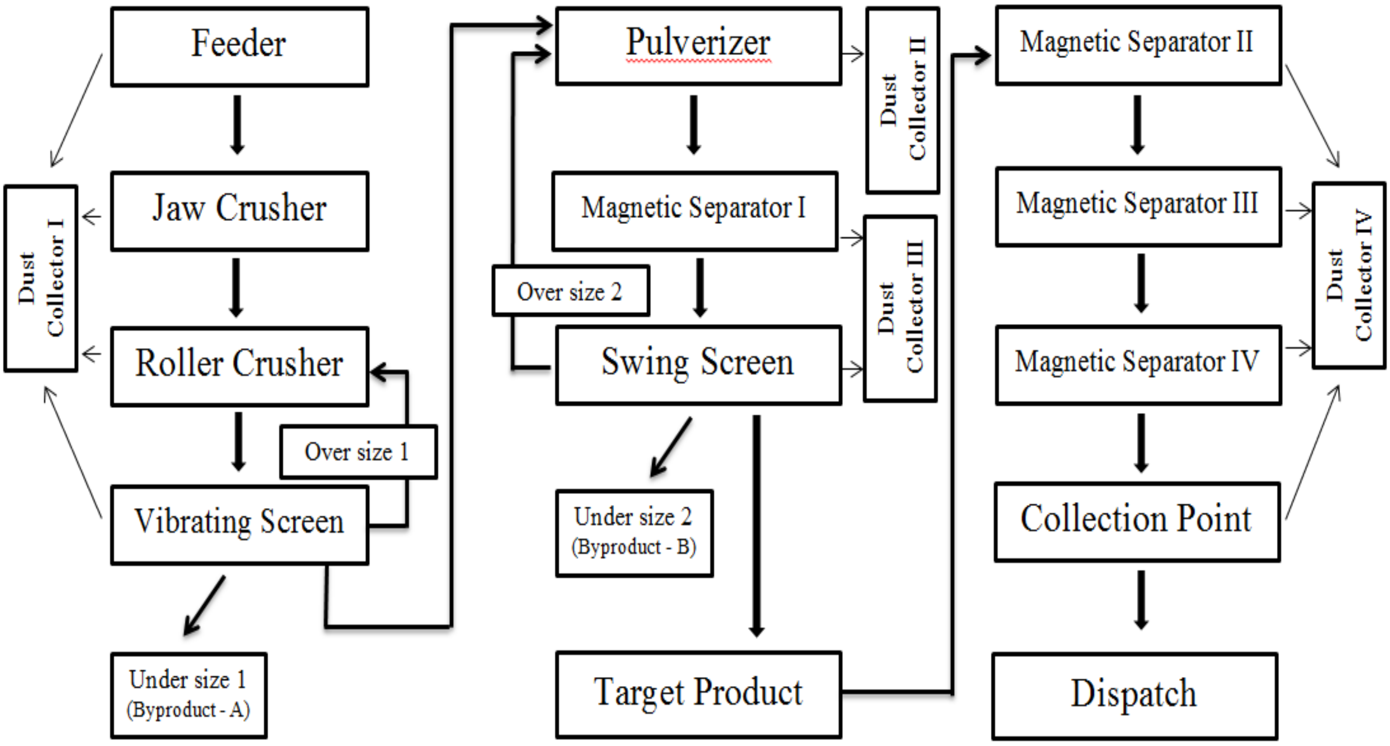


Figure 3.3.1: Quartz processing flow chart at model processing plant

3.3.1.2. Quartz mines

Figure 3.2.1 shows the locations of the seven quartz deposits, selected for the study and scattered in Badulla area. The average processing capacities of the mines are 10 – 15 mt per mine per day and the workforce is around 35 employees per mine. Existing quartz mining flow chart is shown in Figure 3.3.1-1.

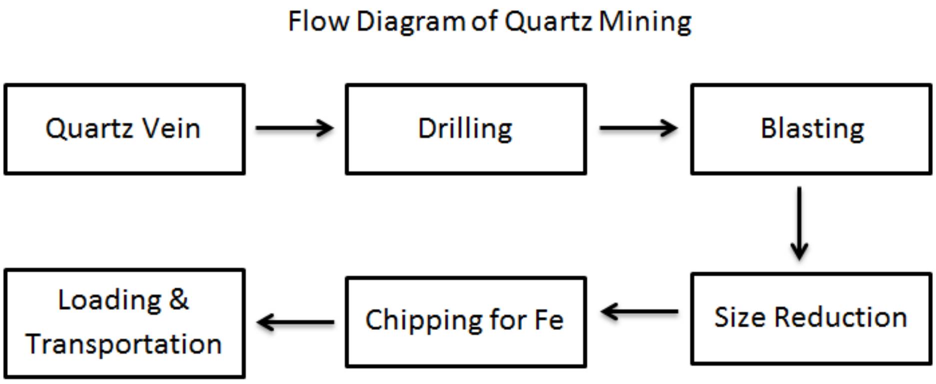


Figure 3.3.1-1: Quartz mining flow chart at selected deposits

3.3.2. Sampling Method

In mining, the quality variation of the quartz output was evaluated based on colour and association of other minerals. Four major colour quartz types namely, Colourless, Milky, Smoky, Rose quartz were selected in the deposits. As Mica and Feldspar associated pegmatites are commonly found in the study area, suitability to use them as a raw material is also evaluated.

After the selection of the potential deposits, removal of top soil was carried out to clear the mine surface. Drilling was carried out for a depth of 3-5 feet and ANFO and Water gel explosives were used for blasting. Resulting boulders were subjected to further size reduction by mechanical and manual labour. Iron strains were removed manually using chip hammers producing 6 × 6 inches quartz lumps.

Ten sub samples were collected from each location and mixed and powdered to select the representative sample in each deposit. Manual sorting was adopted to separate uncontaminated quartz from mica and feldspar associated quartz. Soil contaminated quartz in quarry operation practices was evaluated.

The basic mode of transport from mine to processing plant being a tractor-trailer combination, the Fe contamination of the run-of-quarry in the trailer was identified and the degree of contamination evaluated at the laboratory.

Evaluation of the quartz processing flow chart (Figure 3.3.1) was carried with a view to identify the Fe contamination in the size reduction process at primary and secondary crushing stages. Testing the effectiveness of existing magnetic separators at strategic points and Fe contamination in different size fractions were carried out.

3.3.3. Analysis

Silica content, loss of ignition and metal ion concentration were determined using the methods of IS 1917- part 3, IS 1917- part 1 and modified method of IS 1917 – part 5 respectively.

Dry magnetic separation was carried out using Frantz Isodynamic Magnetic Separator under the magnetic power of 10,000 guess.

3.3.3.1. Reagents and Solutions

Hydrofluoric acid (40%) and Nitric acid (69%) of highest purity available from Sigma- Aldrich and used as received. Doubly distilled deionized water was used throughout. Stock standard solutions of iron, aluminum, calcium, magnesium, sodium, potassium, chromium, manganese, nickel, lead and copper at a concentration of 1000 $\mu g ml^{-1}$ were obtained from Fluka Analytical. Working standard solutions were obtained by appropriate dilution of the stock standard solutions. Standard Reference Materials (SRM) 199, silica brick obtained from the National Institute of Standards and Technology (NIST), U.S. Department of Commerce was used for quality control in each analysis.

3.3.3.2. Apparatus

A Thermo-iCE3500 Atomic Absorption Spectrometer equipped with deuterium background correction was used with iron, aluminum, calcium, magnesium, sodium, potassium hollow-cathode lamps as radiation sources. The operating conditions were those recommended by the manufacturer and a minimum of three standard solutions were used for the calibration in each analysis. Acetylene flow rate, nitrous oxide flow rate, air and the burner height were adjusted in order to obtain the maximum absorbance signal, while aspirating the analyte solutions. Iron, aluminum, calcium, magnesium, sodium, potassium concentrations were determined in ppm range by software using the calibration graph. Concentration of each element in reagent blank and the digested SRM was also determined and these values were used for the calculation of the accuracy of the results. Amount of each element present in the samples were calculated as oxide percentages.

Trace elements, chromium, manganese, nickel, lead and copper were determined using Inductively Coupled Plasma Optical Emission Spectrometer (Agilent 720) with axial view under the operating conditions mentioned in Table 3.3.3.2.

Table 3.3.3.2: Operating conditions of ICP-OES

Condition	**Value**
RF Power	1000 watts
Nebulizer pressure	200 Kpa
Auxiliary Flow	1.5 L/min
Plasma Flow	15.0 L/min
Sample Pump Flow	1.5 mL/min
Sample uptake delay	30 sec
Rinse time	10 sec
Pump rate	15 rpm
Number of replicates	3

Four points calibration was done in ppb range for each element and the concentration of digested samples were determined simultaneously using the calibration graph using the software.

CHAPTER 04
RESULTS AND DISCUSSION

4.1. Introduction

This chapter provides a broad description of the results of the research and a detailed discussion on the results to achieve the research objectives.

4.2. Quartz Types

Quartz veins in the study area are characterized by several varieties such as colourless quartz (rock crystal), smoky quartz, rose quartz, amethyst, citrine and milky quartz. The observed heterogeneity of the quartz type is a result of variation of the trace element content and gas and fluid inclusions (Gotze, 2012). Colourless quartz is usually devoid of any significant amount of trace elements whereas the colours present in smoky quartz, rose quartz, amethyst and citrine are correspondingly due to the presence of trace elements as per Table 4.2 (Santos et al., 2015) and milky quartz is characterized by the presence of gas inclusions (Lin et al., 1997).

Table 4.2: Quartz types and cause of colours

Type of Quartz	Cause of Coloration	Colour
Colourless	NA	NA
Smoky	Al	Ashy
Rose	Cr, Mn, Ti	Rose
Amethyst	Fe	Yellow
Citrine	Fe	Yellow to brown
Milky	Gas inclusions	White

Source: Santos et al., 2015

Quartz types present in the present study area mainly consist of Colourless, Milky, Smoky and Rose quartz. In addition, Feldspar-associated and Mica-associated pegmatite quartz are also common in the study area and has a potential for use as a raw material for advanced applications. Trace element analysis of all types of quartz present in the seven deposits analyzed using ICP–OES and AAS for representative samples are shown in Tables 4.2-1: Milky quartz, Table 4.2-2: Rose quartz, Table 4.2-3: Smoky quartz, Table 4.2-4: Colourless quartz, Table 4.2-5: Mica associated quartz and Table 4.2-6: Feldspar associated quartz.

Table 4.2-1: Trace element content of milky quartz from vein quartz deposits of Badulla, Sri Lanka

Site Name	**ppm**		**ppb**					**ppm**				
	Fe	**Al**	**Cr**	**Mn**	**Ni**	**Pb**	**Cu**	**Ca**	**Mg**	**Na**	**K**	**Ti**
Q 1	13	110	213	189	50	10	460	20	1	10	4	10
	15	110	191	168	70	14	500	14	0	18	10	9
Q 2	23	78	126	180	41		112	8	0	15	22	6
	18	82	172	156	52		132	12	0	18	28	9
Q 3	22	140	184	350	92		280	25	1	10	29	10
	24	115	203	188	103		410	18	3	17	23	12
Q 4	19	112	105	240	78	10	500	22	0	8	10	10
	22	100	93	233	63	8	620	17	0	13	14	11
Q 5	10	130	240	242	60	16	110	18	0	16	21	9
	11	121	198	221	56	12	140	16	1	16	17	9

Table 4.2-2: Trace element content of rose quartz from vein quartz deposits of Badulla, Sri Lanka

Site Name	**ppm**		**ppb**					**ppm**			
	Fe	**Al**	**Cr**	**Cu**	**Mn**	**Ni**	**Pb**	**Ca**	**Mg**	**Na**	**K**
Q 2	27	160	702	593	495	1580	1010	35	0	28	4
	34	168	1784	412	315	1970	1100	32	1	29	3
Q 3	33	205	1288	890	644	1172	1630	55	1	30	0
	31	211	1369	855	596	1065	1595	49	2	38	1
Q 5	29	140						96	2	21	2
	26	131						88	2	26	4
Q 6	34	122	960	1323	696	1248	1870	45	1	21	5
	26	134	689	1180	817	1201	1780	41	1	27	3

Table 4.2-3: Trace element content of smoky quartz from vein quartz deposits of Badulla, Sri Lanka

Site Name	ppm		ppb					ppm			
	Fe	**Al**	**Cr**	**Mn**	**Ni**	**Pb**	**Cu**	**Ca**	**Mg**	**Na**	**K**
Q 6	31	356	808	380	1296	1040	412	31	3	33	6
	27	314	790	236	1640	1059	594	28	2	30	8
Q 4	18	283	272	363	478	1194	363	36	5	27	7
	24	259	261	347	401	1090	315	42	3	29	7
Q 3	31	280	183	390	820	1011	390	39	4	34	3
	28	296	196	331	791	1042	327	50	6	37	5
Q 7	23	238	293	238	991	1020	150	36	4	28	8
	26	231	250	221	1026	992	196	31	4	26	11

Table 4.2-4: Trace element content of colourless quartz from vein quartz deposits of Badulla, Sri Lanka

Site Name	ppm		ppb					ppm				
	Fe	**Al**	**Cr**	**Mn**	**Ni**	**Pb**	**Cu**	**Ca**	**Mg**	**Na**	**K**	**Ti**
Q 1	10	85	220	109	42	21	320	28	2	10	4	9
	8	92	205	110	30	24	432	24	1	11	9	9
Q 3	9	87	226	101	32	27	270	31	0	12	12	6
	7	82	232	118	39	22	230	22	0	10	14	7
Q 4	9	78	252	104	38	19	298	15	0	8	7	8
	12	83	267	113	43	15	330	17	2	9	10	11

Table 4.2-5: Trace element content of mica-associated quartz from vein quartz deposits of Badulla, Sri Lanka

Site Name	ppm		ppb					ppm			
	Fe	**Al**	**Cr**	**Mn**	**Ni**	**Pb**	**Cu**	**Ca**	**Mg**	**Na**	**K**
Q 7	15	240	911	926	1709	1000	911	41	5	28	4
	15	278	934	1062	1409	1050	934	47	3	29	3
Q 3	28	156	844	693	817	1122	797	42	5	28	2
	24	325	891			1120		36	5	28	3
Q 5	19	157	931	865	1161	683	677	29	4	34	1
	27	135	896	831				38	3	34	3

Table 4.2-6: Trace element content of feldspar-associated quartz from vein quartz deposits of Badulla, Sri Lanka

Site Name	ppm		Ppb					Ppm			
	Fe	**Al**	**Cr**	**Mn**	**Ni**	**Pb**	**Cu**	**Ca**	**Mg**	**Na**	**K**
Q 4	303	740	868	18405	1175	7675	1375	60	10	40	0
	313	743	870	16887	1661	8683	1660	54	8	38	1
Q 6	751	1715	1421	518	860	2643	887	53	11	42	3
	722	1738						59	12	41	5
Q 7	740	1959	1176	480	807	2015	741	61	7	36	5
	743	1905						65	8	34	7

Blankenburg et al., (1994) and IOTA, (2017) present permissible levels of chemical composition in quartz raw material for different types of industrial applications of quartz in Table 4.2-7.

Figure 4.2.1: Major 6 Types of Quartz in Badulla Area

Table 4.2-7: Permissible levels of chemical composition in quartz raw material for different types of industrial applications of quartz

	Fiber Optics	**Chemically Reinforced Glass**	**Special Optical Glass**	**Quartz Glass for Semiconductors**	**Window Glass**	**Bottle Glass**
SiO_2	>99.9 wt%	>99.8 wt%	>99.8 wt%	>99.999 wt%		
Fe_2O_3 (ppm)	<2.0	<9	<20	< 0.1	<700	3500-8500
TiO_2 (ppm)	<1.5	< 20	<25			
Al_2O_3 (ppm)	<80	< 350	<500	< 3		
Cr_2O_3 (ppm)	<0.01	<0.3	<0.1	<0.01		
CoO(ppm)	<0.05		<0.05			
CuO(ppm)	<0.05	< 1	<0.1	<0.01		
MnO(ppm)	<0.1	< 0.5	<1	<0.01		
NiO(ppm)	<0.1	<0.2	<0.15	<0.01		
V_2O_5 (ppm)	< 0.5		< 15			

Source : Blankenburg et al., 1994 ; IOTA, 2017

In this research, the potential for use of Sri Lankan vein quartz for specific high tech industries was assessed using the standards given in Table 4.2-7. According to Table 4.2-7, SiO_2 level and critical impurities (Fe, Ti, Al, Cr, Co, Cu, Mn, Ni and V) with maximum permissible limit for high tech applications were evaluated. For example, quartz glass for semiconductors requires stringent trace element content whereas for bottle glass, requirements are lower.

4.2.1. SiO_2

SiO_2 content or the purity level of quartz raw material is the most important indicator for using quartz as a raw material for high tech industry. Known high tech application requires SiO_2 content over and above 99.8% (refer Table 4.2-7). SiO_2 content of the present study varies from 99.5% to 99.9% with colourless and milky quartz, having an average of 99.9%, whereas smoky, rose and mica associated quartz having an average of 99.8% and feldspar associated quartz having an average of 99.5%.

4.2.2. Trace Element Content and Variation

Under this topic industrially important trace elements such as Fe, Al, Cr, Mn, Ni are subjected to further discussion.

4.2.2.1. Fe

Higher Fe content is the cause of variations in properties of glass, causing easy cracking. In thicker glass, the colour changes to greenish or brownish due to the presence of Fe (Banza et al., 2006). Higher Fe content also compromises the efficiency in solar silicon processing (Dhamrin et al., 2009), reduces transparency in UV region and its radiation resistance and reduce performance in UV light-induced water purification (Griscom, 2011).

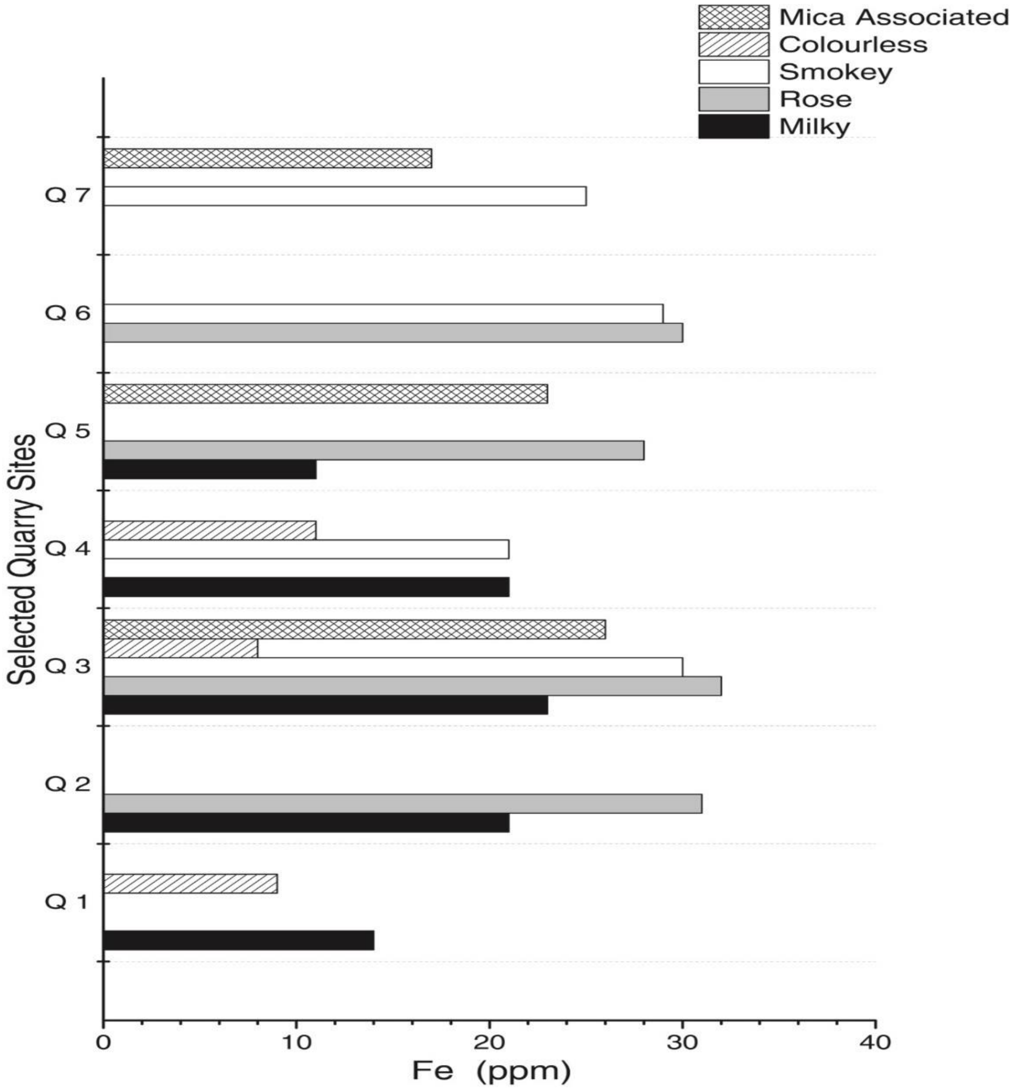


Figure 4.2.2.1: Fe concentration in selected vein quartz deposits in Badulla

Fe concentration of milky, smoky, rose, colourless and mica-associated quartz are shown in Figure 4.2.2.1. Fe content of Milky quartz in the present study varies from 10 to 24 ppm with an average of 17.7 ppm. Even though the average Fe levels of deposits, Q1 (14 ppm) and Q5 (11 ppm) in the present study are suitable for special optical glass , Cr and Cu contents need to be removed to a permissible level using advance mineral processing techniques (refer Table 4.2-7). Milky quartz with higher contents of Fe in the studied deposits offers a possibility to reduce Fe content below 9 ppm with the application of physical separation processing techniques. On the other hand, milky quartz in deposit Q5 has a very low Fe content around, 10 ppm that can easily be improved to the permissible level of Fe content in raw material for chemically reinforced glass carrying a higher demand as “tempered glass” (refer Table 4.2.2.1 in Appendix 1). In the present study, colourless quartz was found to contain the lowest Fe content ranging from 7 to 12 ppm with an average of 9.2 ppm almost suitable as a raw material for chemically reinforced glass. In the case of rose quartz, Fe content varies from 26 to 34 ppm with an average of 30 ppm. Therefore, rose quartz in the study area can directly be used for lower value products such as color glass and bottle glass manufacture (Santos et al., 2015). Smoky quartz has a Fe content similar to that of rose quartz ranging from 23 to 31 ppm with an average of 26 ppm. Therefore, Fe content in smoky quartz meets the required standard for manufacturing crystal glass and solar cell cover glass (Burrows and Fthenakis, 2015). Mica associated quartz has a Fe content ranging from 15 to 28 ppm with the exception of deposit Q7 with an Fe content less than 20 ppm, that can be used as a source for special optical glass with respect to its Fe content. On the other hand, quartz associated with Feldspar has a high Fe content above 300 ppm thus, disqualifying it from using as a raw material for high tech applications (refer Figure 4.2.2.1-1 in Appendix 2). However, physical separation of quartz from feldspar was carried out by manual and mechanical breaking, making feldspar contamination a possibility in the quartz phase, resulting in a higher Fe content in feldspar associated quartz.

4.2.2.2. Al

In addition to Fe, other trace elements such as Al, Cr, Mn and Ni content also play an important role in determining the properties of the quartz based products (Dash et al., 2004). Al is also a key trace element that controls the suitability of raw material for the manufacture of semiconductors, fiber optics, chemically reinforced glass and special optical glass varieties (Huang et al., 2013). At high temperature, higher Al levels change the viscosity of molten glass raw materials affecting the uniformity of resultant glass product (Muller et al., 2002). In addition, the glass transition temperature is also affected due to the variation of Al content (Kim and Hwang, 2011). In LCD glass, high homogeneity of the display is also affect by high Al levels (Kim, 2013). Studies reveal that Al preferentially located in the quartz crystal lattice itself, and not in other minerals present in quartz as inclusions or adsorbed material. Such lattice located impurities are especially difficult to remove. Quartz samples with Al levels reaching values higher than 100 ppm will hardly be purified into commercial levels (Rakov, 2006, Gotze, 2009).

In the present study, Al content in colourless quartz, milky quartz, rose quartz, smoky quartz, mica associated quartz and feldspar associated quartz varies within the limits of 78 to 92 ppm, 78 to 140 ppm, 122 to 211 ppm, 230 to 356 ppm, 157 to 325 ppm and 740 to 1959 ppm respectively (refer Table 4.2.2.2 in Appendix 3). Therefore, colourless quartz, milky quartz and rose quartz deposits have an Al content suitable for chemically reinforced glass manufacture (refer Table 4.2-7) whereas, in the case of smoky quartz except in deposit Q6, all the other deposits have a marginal Al content with in the permissible limit (refer Figure 4.2.2.2). Feldspar associated quartz has a significantly higher Al values and according to Manfredini and Hanuskova (2012), suitable as a raw material for ceramic industry.

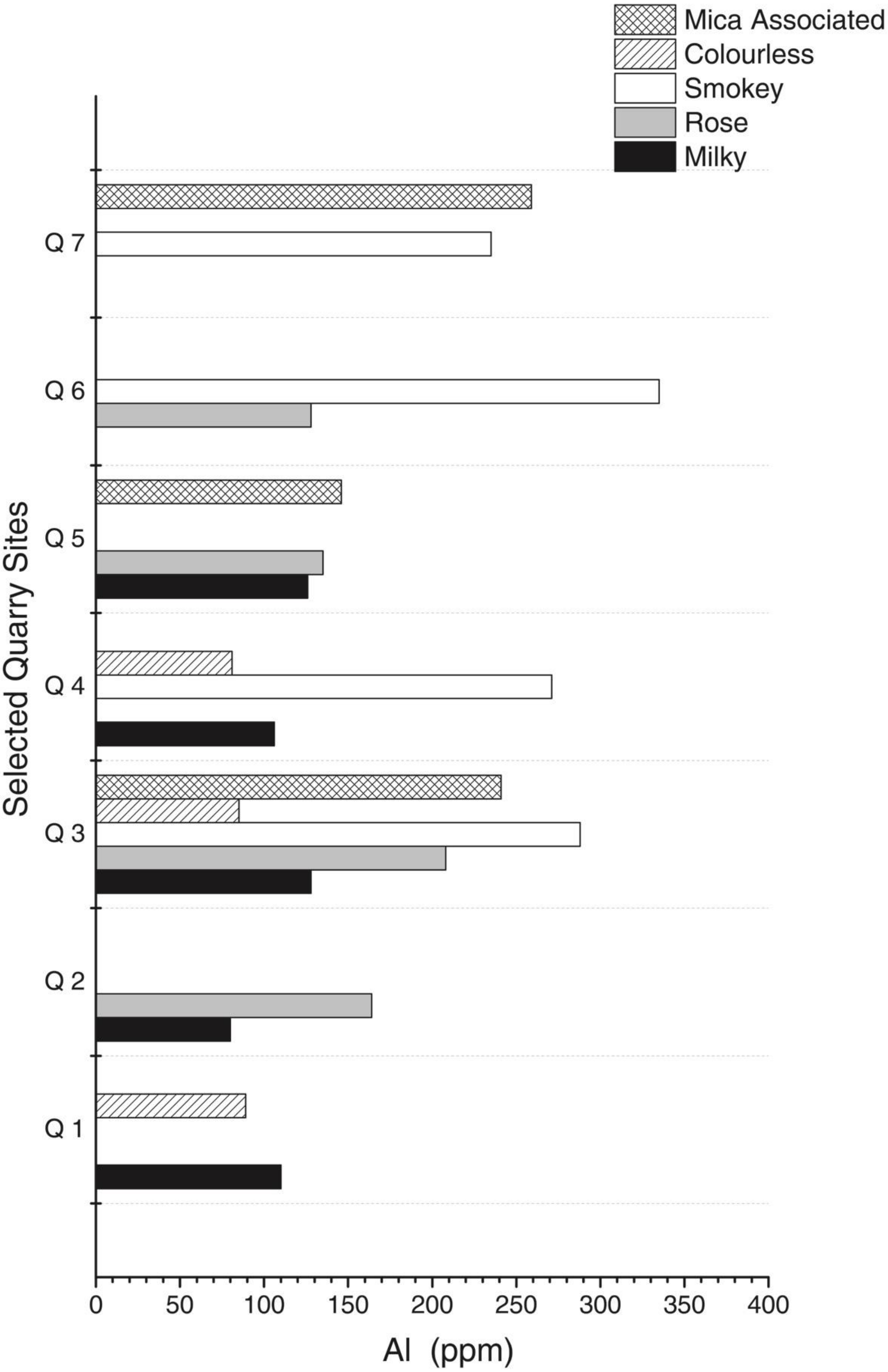


Figure 4.2.2.2: Al concentration in selected vein quartz deposits in Badulla

4.2.2.3. Cr

Cr gives a green and purple colouration to the silica glass that reduces its transparency and transmission properties (Mackey, 1963). Therefore, presence of Cr in glass has to be controlled by various techniques and especially rose quartz contamination in processing has to be avoided in clear glass industry (Gemeinert et al., 1992).

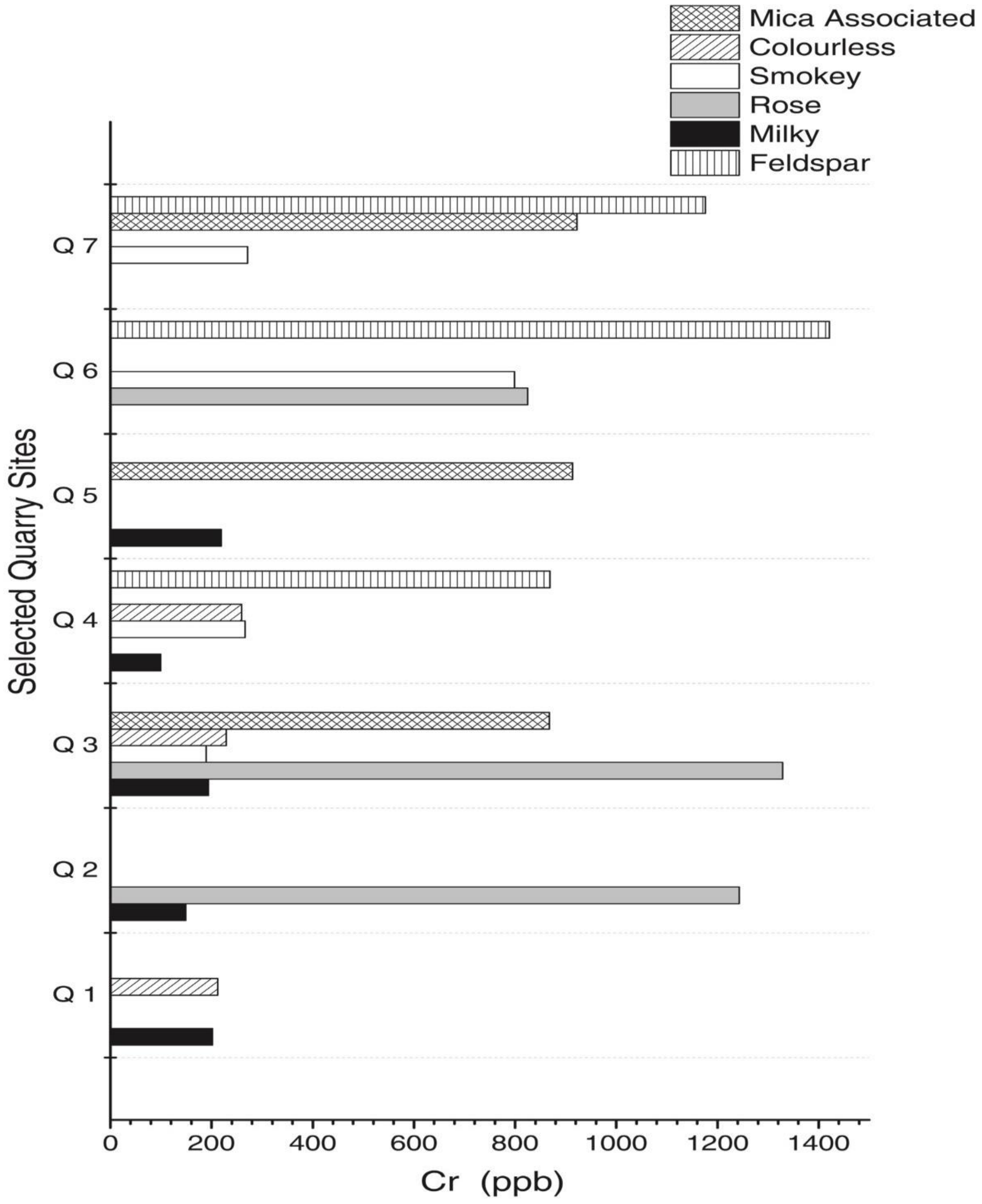


Figure 4.2.2.3: Cr concentration in selected vein quartz deposits in Badulla

In the present study, Cr content in colourless quartz, milky quartz, rose quartz, smoky quartz, mica associated quartz and feldspar associated quartz varies within the limits of 0.20 to 0.27 ppm, 0.09 to 0.24 ppm, 0.7 to 1.80 ppm, 0.18 to 0.81 ppm, 0.84 to 0.94 ppm and 0.86 to 1.42 ppm respectively (refer Table 4.2.2.3 in Appendix 4). Therefore, all the colourless and milky quartz quarries have Cr content suitable for chemically reinforced glass manufacturing (refer Table 4.2-7) whereas in the case of smoky quartz, all quarries except Quarry Q6 have a lower Cr content. Rose quartz, mica-associated and feldspar associated quartz have higher Cr values than the allowable limits and therefore, not suitable as a raw material for clear glass industry (refer Figure 4.2.2.3).

4.2.2.4. Mn

In the thin film industry, Mn concentrations change the conductivity of the film product (Zhang et al., 2012). In producing High Purity Quartz (HPQ) with flotation techniques, Mn depresses quartz in flotation; the recovery of quartz decreases with higher Mn concentrations due to adsorption and precipitation on quartz surface (Yang et al., 2014). In glass industry, oxides of Mn give a colouration (purple) of the silica glass that reduces its transparent properties (Mackey, 1963).

In the present study, Mn content in colourless quartz, milky quartz, rose quartz, smoky quartz, mica associated quartz and feldspar associated quartz varies within the limits of 0.18 to 0.3 ppm, 0.2 to 0.4 ppm, 0.3 to 0.8 ppm, 0.2 to 0.4 ppm, 0.7 to 1.1 ppm and 0.5 to 18 ppm respectively respectively (refer Table 4.2.2.4 in Appendix 5). Therefore, in some quarries, mica-associated and feldspar associated quartz have higher Mn values than 0.5 ppm which make them unsuitable as a raw material to chemically reinforced glass (refer Figure 4.2.2.4). But, in the study area, colourless, milky, rose and smoky quartz quarries have a Mn content suitable as a raw material for chemically reinforced glass and special optical glasses whereas in the case of fiber optics and quartz glass for semiconductors which makes unsuitable as a raw material due to presence of higher Mn levels than permissible limits (refer Table 4.2-7).

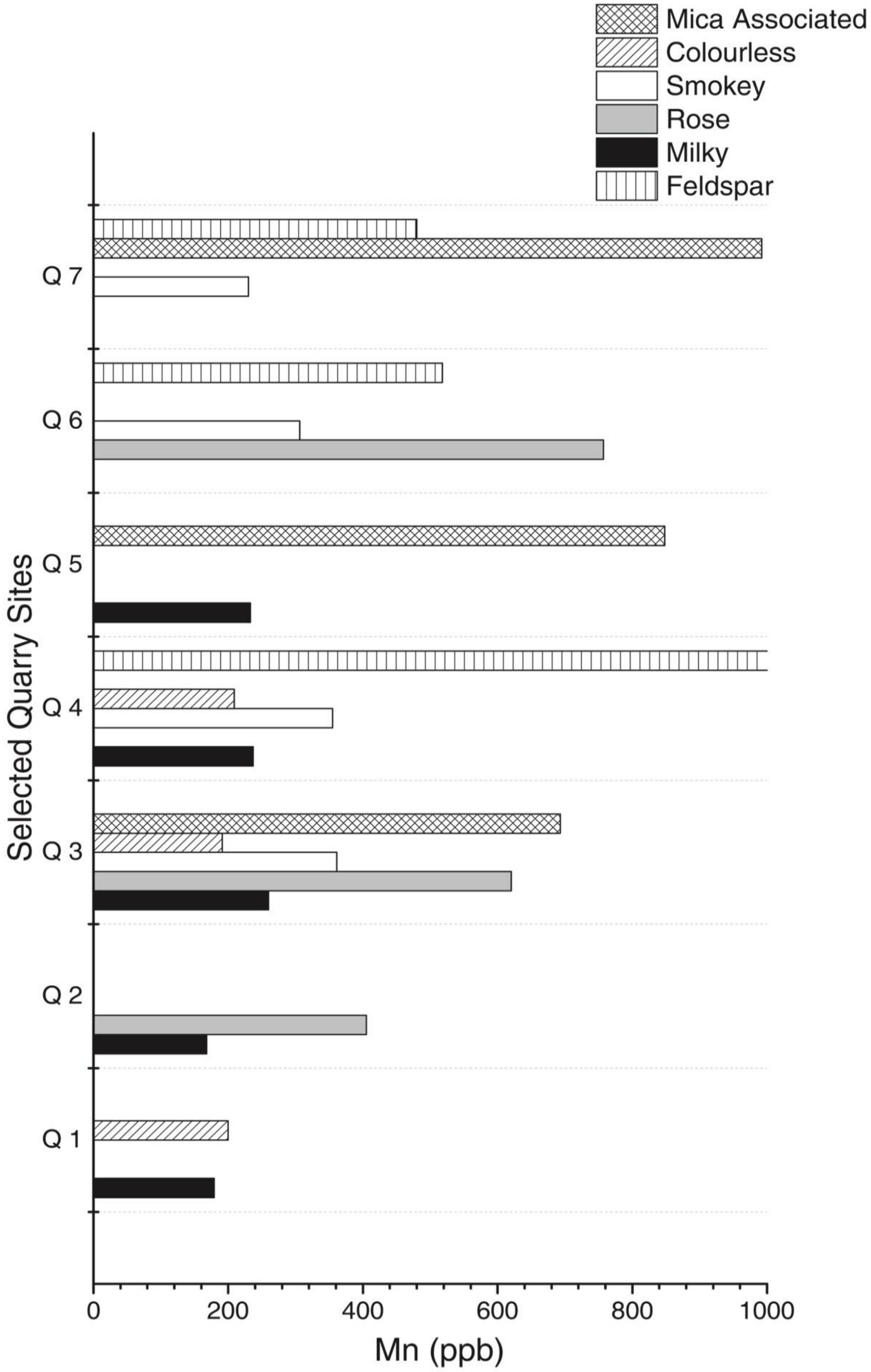


Table 4.2.2.4: Mn concentration in selected vein quartz deposits in Badulla

4.2.2.5. Ni

Ni gives a blue or violet colouration to silica glass that reduces its transparency and transmission properties (Mackey, 1963). Therefore, presence of Ni in glass industry has to be controlled and especially in processing while sieving, Ni contamination can occur due to stainless steel meshes (Santos et al., 2015). Therefore, naturally Ni low deposits and Ni free sieves in quartz processing are important in producing raw material for glass industry.

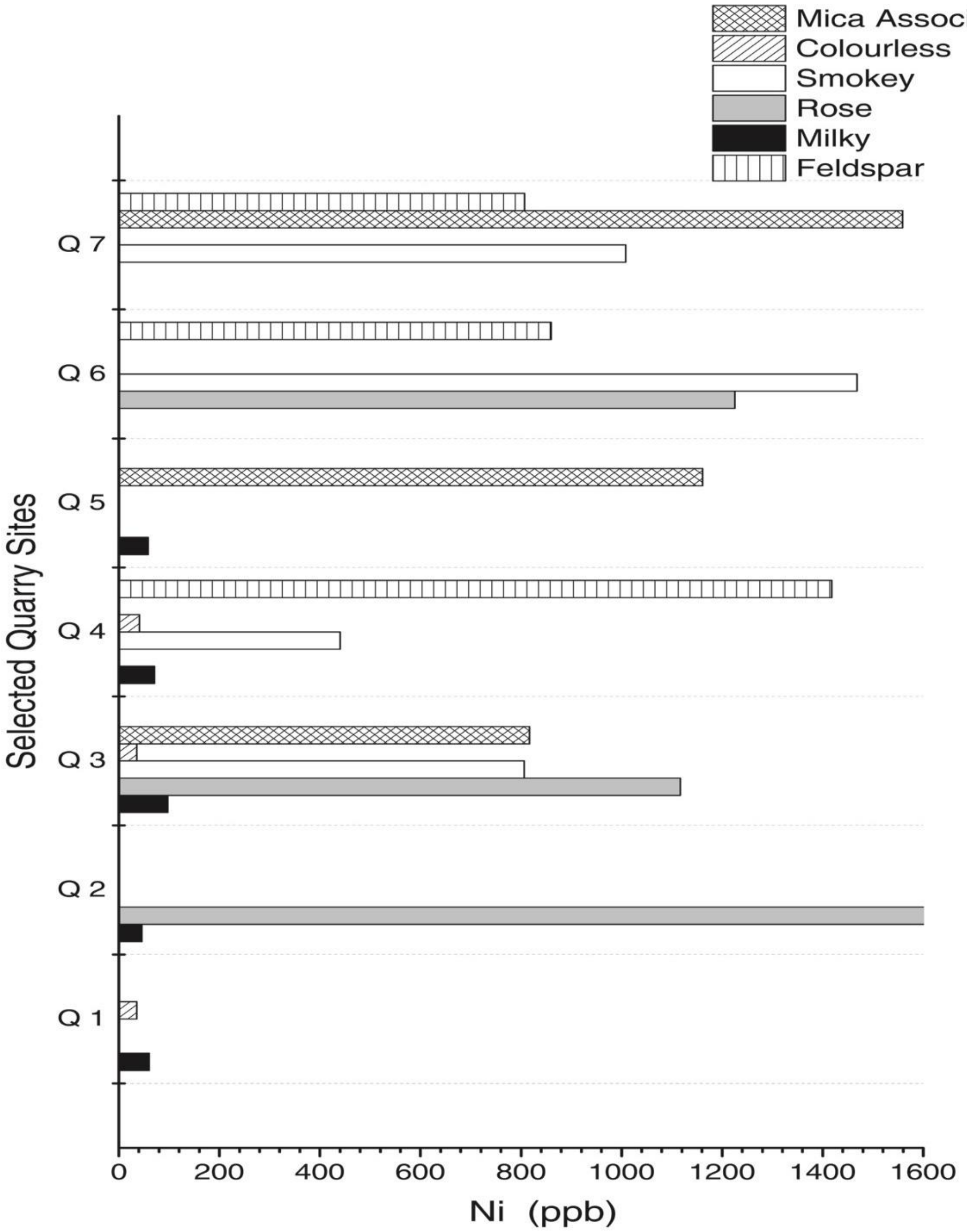


Figure 4.2.2.5: Ni concentration in selected vein quartz deposits in Badulla

In the present study, Ni content in colourless quartz, milky quartz, rose quartz, smoky quartz, mica associated quartz and feldspar associated quartz varies within the limits of 0.03 to 0.04 ppm, 0.05 to 0.1 ppm, 1.0 to 2.0 ppm, 0.4 to 1.6 ppm, 0.8 to 1.7 ppm and 0.7 to 1.7 ppm respectively (refer Table 4.2.2.5 in Appendix 6). Therefore, only colourless and milky quartz quarries have Ni content suited for chemically reinforced glass manufacturing (refer Table 4.2-7). Ni concentration of milky, smoky, rose, colourless, mica-associated and feldspar-associated quartz are shown in Figure 4.2.2.5.

4.3. Gas and Fluid Inclusions

Gas and fluid inclusions are also present in quartz in the study area. Natural quartz commonly contains micro-inclusions less than 1 µm of minerals, silicate melt and fluids (Kitamura et al., 2007). If the intensity of inclusions is high, the influence on the chemical quality of quartz raw materials is greater. Primary Fluid inclusions, the most common inclusions in quartz are formed during crystal growth and secondary fluid inclusions can occur during the resealing of cracks in a pre-existing crystal when mineralizing fluids penetrate in to quartz (Van den Kerkhof and Hein, 2001). However, fluid inclusions and their dissolved components can be removed during processing by thermal treatment and calcination (Haus, 2005). In the glass industry, gas and fluid inclusions generate bubbles during fusion processes and compromise both mechanical and optical properties of finished glass products (Kitamura et al., 2007). Though water is the most common fluid present, carbon dioxide, methane, heavier hydrocarbons and nitrogen can also occur. Na, K, Mg and Ca from fluid inclusions are common as a major contamination source. Therefore, levels of Na, K and Ca can be used as an indicator to identify gas and fluid contamination. In the present study, analysis of milky and colourless quartz shows Na, K, Ca levels less than 20, 30 and 25 ppm respectively whereas rose quartz, smoky quartz, mica-associated quartz and feldspar-associated quartz types show more than 30 ppm. Thus, milky and colourless quartz in study area have less contamination with gas and fluid inclusions in the lattice structure.

4.4. Chipping Quartz Lumps

Usually accumulated impurities are removed by physical methods as removal by chemical methods may disperse the impurities throughout the mass. Therefore, as a common practice, iron stains are chipped out manually in quartz industry to reduce Fe contamination. A Fe stain in milky quartz is shown in Figure 4.4. Current study shows that Fe level in the iron stained chips as high as 350 ppm (shown in Table 4.4). Comparison of Fe concentration in Fe stained quartz chips and cleaned lumps are shown in Figure 4.4-1.

Figure 4.4: Fe stains in milky quartz in selected vein quartz deposits of Badulla

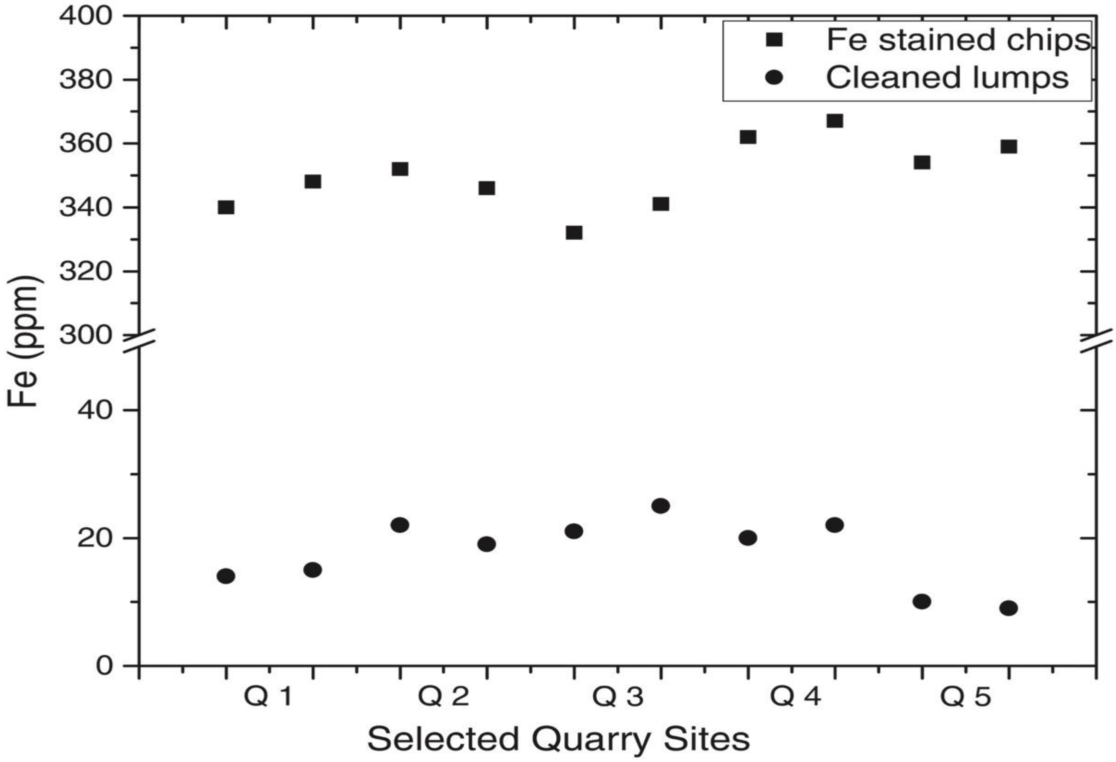


Figure 4.4-1: Graphical comparison of Fe concentration in Fe stained quartz chips and cleaned lumps

Table 4.4: Fe concentration of Fe stained quartz chips and cleaned quartz lumps

Site Name	**Fe ppm**	
	Fe stained chips	**Cleaned lumps**
Q 1	340	14
	348	15
Q 2	352	22
	346	19
Q 3	332	21
	341	25
Q 4	362	20
	367	22
Q 5	354	10
	359	9

4.5. Soil Contamination

In the mining stage, quality control is essential to reduce soil contamination with quartz raw material. Especially, during the rainy season, size reduction of quartz by mechanical and manual means without soil contamination is difficult but it ensures producing high quality raw material. With soil contamination, critical trace element content increases and becomes highly variable from sample to sample (shown in Figure 4.2). Only from washing and cleaning, it is difficult to reduce impurities to desired levels due to adsorption and absorption of impurities into micro cracks (Parks, 1984). In this study, chemical analyses of soil contaminated quartz were carried out with results showing Fe level increasing up to 400 ppm (shown in Table 4.5).

Table 4.5: Trace element contents of soil contaminated quartz selected vein quartz deposits of Badulla

Site Name	ppm		ppb				ppm					
	Fe	**Al**	**Cr**	**Ni**	**Pb**	**Cu**	**Ca**	**Mg**	**Na**	**Mn**	**K**	**Ti**
Q 1	392	623	935	699	3478	723	810	312	137	5	153	85
	387	735	954	834	2261	738	508	281	221	7	159	78
Q 2	385	577	1209	1069	3207	746	1122	219	361	5	158	92
	366	706	943	1366	2802	863	636	221	227	4	159	87
Q 3	403	679	843	683	2619	851	553	321	203	9	172	68
	406	614	975	686	2160	839	546	331	125	9	191	76
Q 4	413	698	1118	1160	2190	908	650	164	162	7	197	91
	401	720	1503	1024	2968	821	754	127	215	7	176	71
Q 5	412	898	1185	733	3284	671	791	136	597	7	254	69
	381	751	1016	428	3206	692	767	164	386	6	220	77

Therefore, prior to processing, chipped lumps were subjected to jet water washing, draining and sun drying. Therefore, reducing soil contamination in the course of mining and transportation is important to produce quartz raw material for high products.

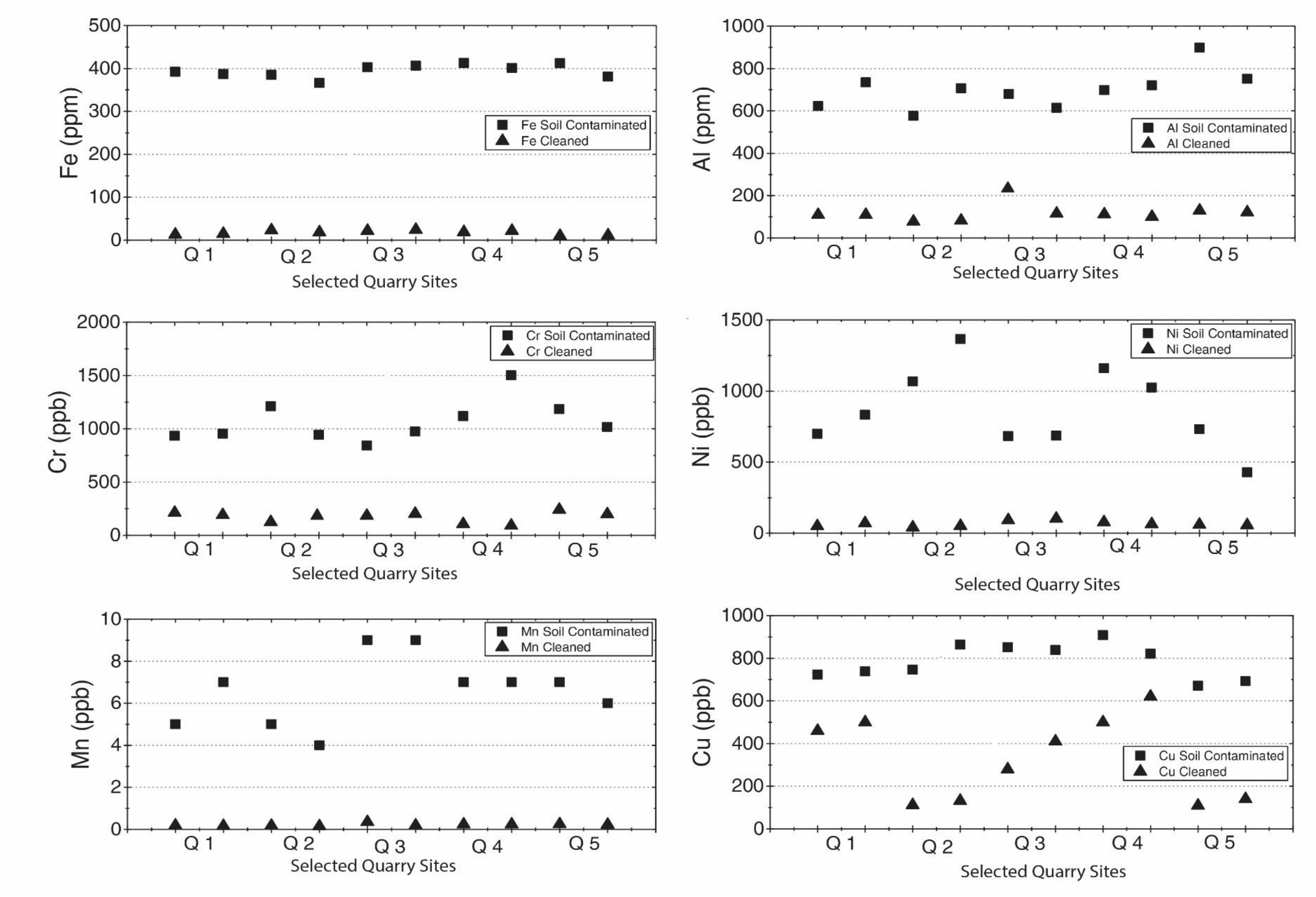


Figure 4.5: Comparison of the key trace element content of soil contaminated and clean quartz

4.6. Contamination in Transportation

As iron lined tractor trailers and trucks are mostly used in local quartz industry for transportation from mine to the processing plant, Fe contamination of chipped lumps in the course of transportation is very high. In rainy conditions, Fe contamination can increase to high levels as a result of the liners of the conveyance becoming wet. Further, formation of a rust layer during nonworking days enhances the degree of Fe contamination. In the present study, tested contamination in the course of transportation shows an increase Fe level up to 170 ppm (shown in Figure 4.6).

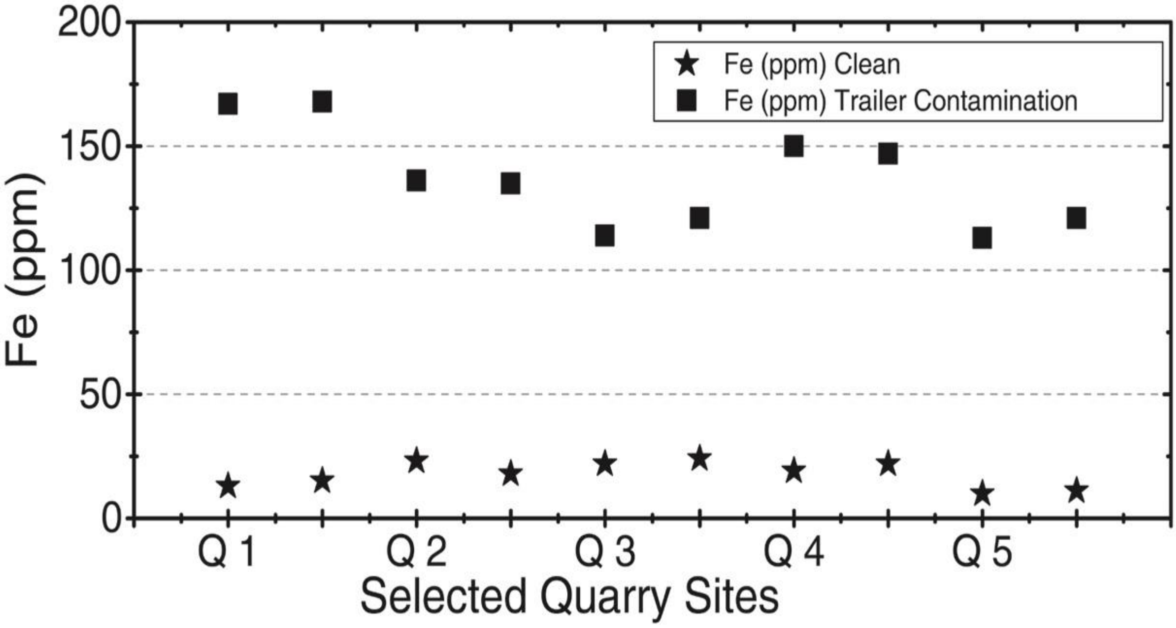


Figure 4.6: Comparison of Fe concentration in trailer contaminated quartz and clean quartz

4.7. Removal of Fe Using Size Reduction

According to tables 4.2-1 to 4.2-6, colourless and milky quartz can be used as raw material for high-end glass industry. In the study area, colourless quartz is not available in large quantities. Therefore, to ensure a stable raw material supply of large scale exports over the years only milky quartz veins are available. Hence, Milky quartz is selected for further processing in an existing quartz processing plant. In the present study, milky quartz lumps were subjected to comminution by jaw and roller crusher with downstream separation using a vibration screen to separate it in to size fractions of oversize (+ 10 mm), 1 to 10 mm and below 1 mm. Oversize fraction was re-fed to the roller crusher whereas 1 to 10 mm size was taken as semi processed raw material and below 1 mm as a byproduct-A. Magnetic separation results, carried out using dry isodynamic magnetic separator show that 1 to 10 mm fraction contained hardly any Fe whereas the byproduct-A contained Fe levels over 50 ppm (refer Figure 4.7). Usually mineral impurities are fine grained, and most are secondary minerals which is easily be pulverized into finer material. According to Andres et al., 1999; Dal Martello et al., 2011a, b, most of the mineral impurities in vein quartz are located along crystal boundaries and 1 to 10 mm size fraction showed a reduced Fe level due to breakage during crushing and grinding happens along weaker grain boundaries and fractures liberating finer Fe bearing impurities. These finer bearing impurities accumulate in below 1 mm byproduct-A fraction along with machine wear and tear. Resulted Fe concentrations are shown in Table 4.7.

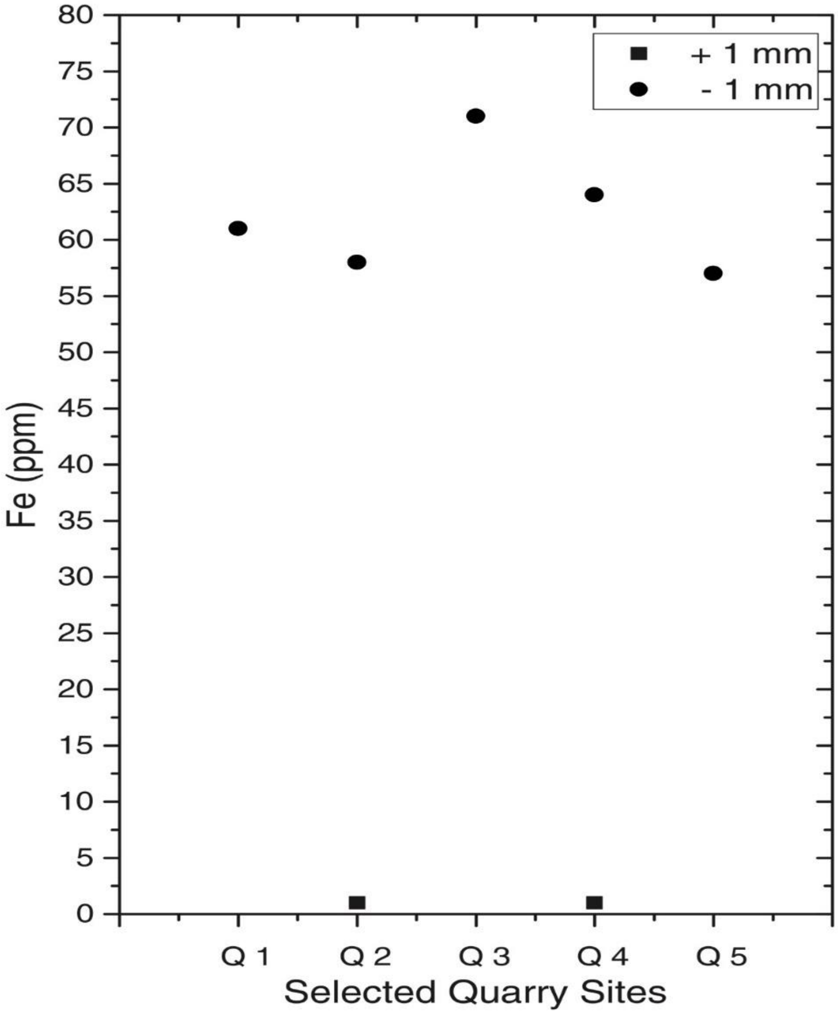


Figure 4.7: Comparison of Fe concentration of grit products +1 mm and -1 mm

Table 4.7: Fe concentrations of grit products +1 mm and – 1 mm

Site Name	Fe (ppm)	
	+1 mm	**-1 mm**
Q 1	N/D	61
Q 2	1	58
Q 3	N/D	71
Q 4	1	64
Q 5	N/D	57

Therefore, due to high Fe concentration, byproduct-A (-1 mm fraction) cannot be used as a raw material to produce high end glass products, but it is suitable as a raw material in sheet or bottle glass industry (Blankenburg et. al.,1994). Whereas lower Fe containing 1 to 10 mm size fraction can be used as raw material for chemically reinforced glass after meeting the size requirement. Extracted 80 to 300 micron powder portion through pulverizing above 1 to 10 mm size portion shows hardly any Fe whereas below 80 micron byproduct-B contained Fe levels over 16 ppm (refer Figure 4.7-1). Again, the remaining mineral impurities and machine wear and tear further liberated due to powdering, accumulated in the below 80 micron byproduct-B. Resulted Fe concentrations are shown in Table 4.7-1.

Table 4.7-1: Fe concentrations of grit products 80- 300 µ and – 80 µ

Site Name	Fe (ppm)	
	80- 300 µ	**< 80 µ**
Q 1	N/D	18
Q 2	1	21
Q 3	N/D	16
Q 4	N/D	22
Q 5	1	19

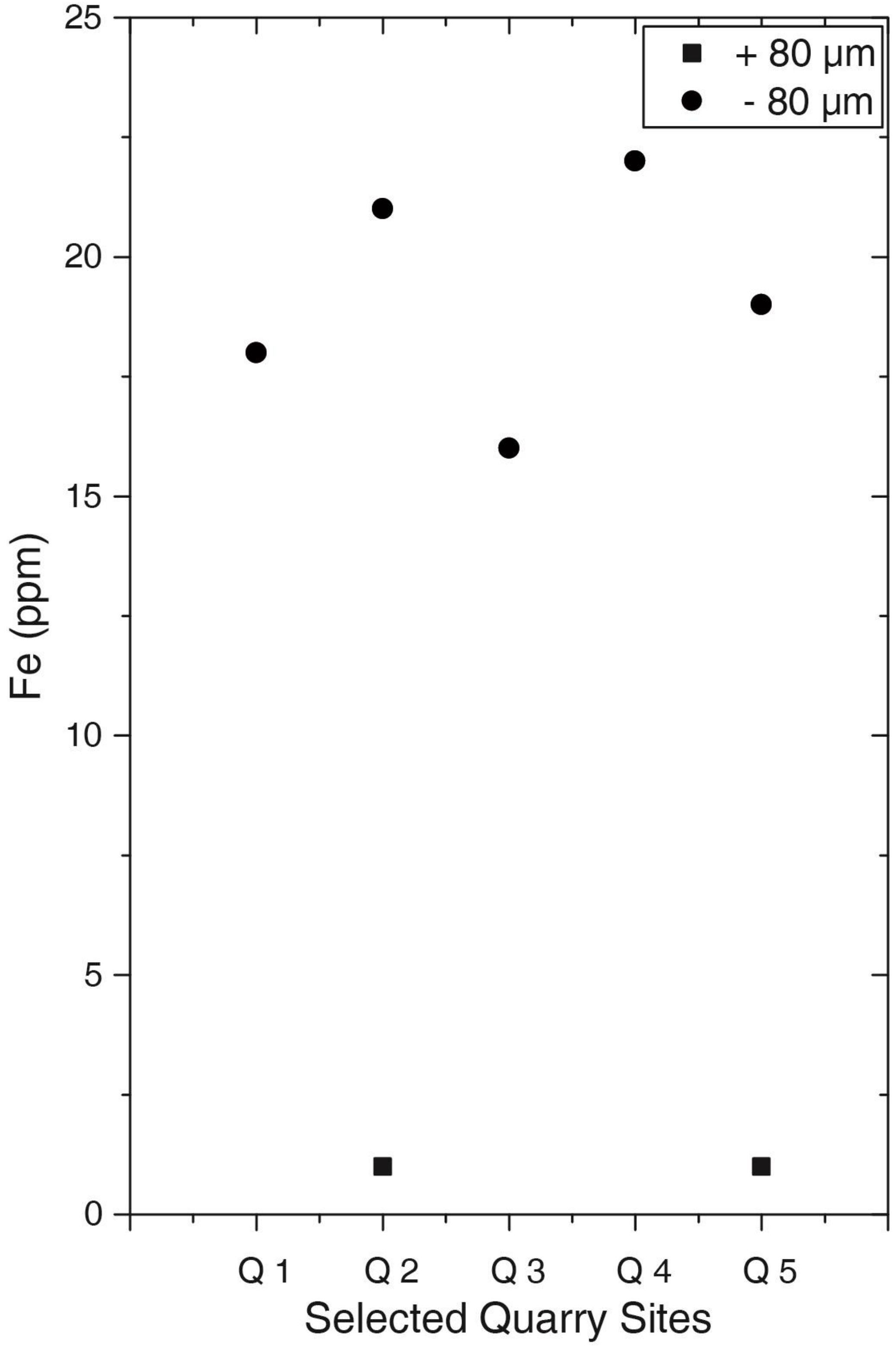


Figure 4.7-1: Comparison of Fe concentrations of grit products 80- 300 µ and – 80 µ measured using isodynamic magnetic separator

4.8. Removal of Fe Using Magnetic Separators

For further reduction of Fe, using magnetic separators (24 trays of 10,000 guess each) for 80 to 300 micron powder products results reduced Fe levels to less than 9 ppm in all samples (Refer Table 4.8). Comparison of Fe levels before and after magnetic separation with reference to maximum permissible limit (9 ppm) of chemically reinforced glass is shown in Figure 4.8.

Table 4.8: Comparison of Fe concentration before and after magnetic separation

Quarry Name	Fe Content (ppm)	
	Before Magnet	**After Magnet**
Q 1	13	7.3
	12	5.7
Q 2	15	5.8
	17	5
Q 3	16	5.1
	14	7.4
Q 4	14	5.3
	17	5.8
Q 5	11	6.5
	12	7.7

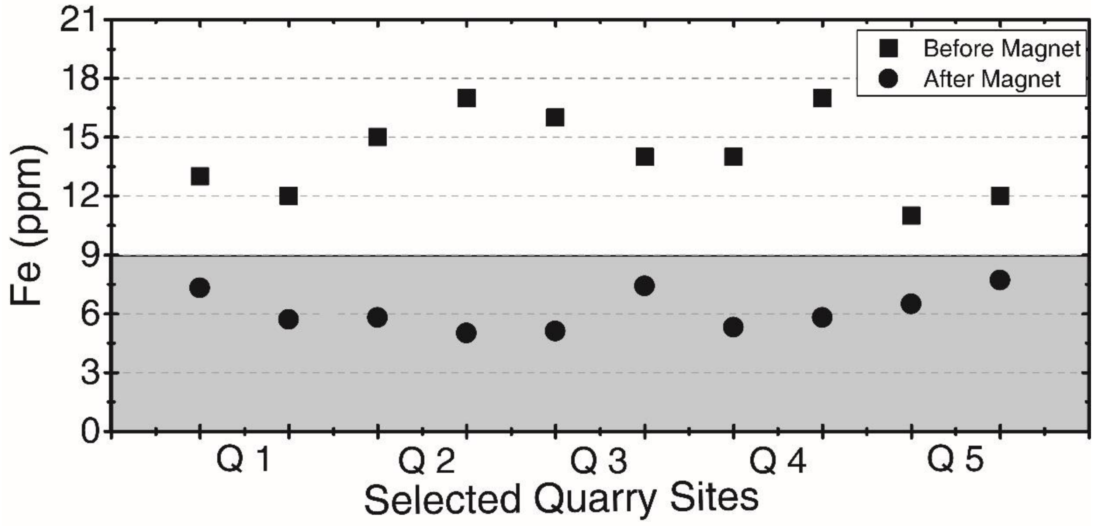


Figure 4.8: Comparison of Fe levels before and after magnetic separation with reference to maximum permissible limit (9 ppm) of chemically reinforced glass

CHAPTER 05
CONCLUSION AND RECOMMENDATION

5.1. Conclusions

Selective mining and quality control in mining, transportation and processing activities lead to production of industry specific quartz raw material.

- Transparent and Milky Quartz in the observed quarries have the lowest trace element contents and their natural quality is close to the requirements of Chemically Reinforced Glass.
- Smoky Quartz has higher values of Al and Ni contents and can be used for sheet glasses, automobile and solar cells cover glass.
- Rose Quartz has higher values of Mn, Cr, Ni and Ti and can be used for colored glasses.
- Mica-associated Quartz has higher values of Cr and Ni and can be used for solar cells cover glass.
- Feldspar-associated Quartz has higher values of almost all trace elements and therefore suitable for ceramic industry.
- Mixing the raw material of various quartz types reduces the quality.
- Soil contamination need to be minimized during mining and transportation.
- Maintaining a surface devoid of oxidized crust in material transportation iron lined vehicles and thorough cleaning after holidays reduce the Fe contamination.
- Removal of the finest fraction in each crushing step during processing reduces the Fe content and enhances the purity of the product.
- Magnetic separation after powdering further reduces the Fe content.

5.2 Recommendations

Recommendations for the methods adopted in preventing iron contamination and removal process,

Iron contamination prevention at the mine site;

- Construction of a silica bed in the site closer to the extraction point for temporary storage of the blasted quartz to prevent soil contamination at the mine site.

- Tractor-trailer travel path made of concrete or metal should be parallel to the silica bed at the mine site.
- Mined material should be dumped at one end of the silica bed while workmen power with plastic buckets can be utilized to load the tractor trailers.
- Loader used for material loading on the bed should be well cleaned and serviced to prevent any possible contamination of the material.
- Lining of the tractor trailers should have made of wood, fiber, rubber or plastic which should be periodically washed off and dried.

Iron removal at the raw material storage site at the factory premises;

- Storage yard should be cleaned periodically.
- For the transportation from the yard to bin iron-lined tractor trailers can be used, which should be periodically washed off and dried.

Prevention of iron contamination at the processing plant;

- All the machinery should be cleaned of dust, grease and all extraneous matter before the start of production
- Conveyor belt covers to be removed, cleaned and fixed once a month
- Cleaning the dust collectors and dust bags should be conducted at every week or as the occasion demands
- Cleaning of factory floor and entrance every day
- Proper ventilation system should be implemented for factory interior by installing sufficient number of ventilation fans to ensure proper air quality. Delivery ducts endings should be attached to wet scrubbers
- The main door must be covered with heavy duty hard polythene strips to prevent dust contamination
- Special working overalls and footwear should be issued to workman employed within the processing plant premises

Prevention techniques of iron in quartz processing plant are describe in Appendix 8.

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Appendix

Appendix 1

Table 4.2.2.1: Fe concentration in selected vein quartz deposits in Badulla

Site Name	Milky	Rose	Smokey	Transparent	Mica	Feldspar
Q 1	13			10		
	15			8		
Q 2	23	27				
	18	34				
Q 3	22	33	31	9	28	
	24	31	28	7	24	
Q 4	19		18	9		303
	22		24	12		313
Q 5	10	29			19	
	11	26			27	
Q 6		34	31			751
		26	27			722
Q 7			23		18	740
			26		15	743

Appendix 2

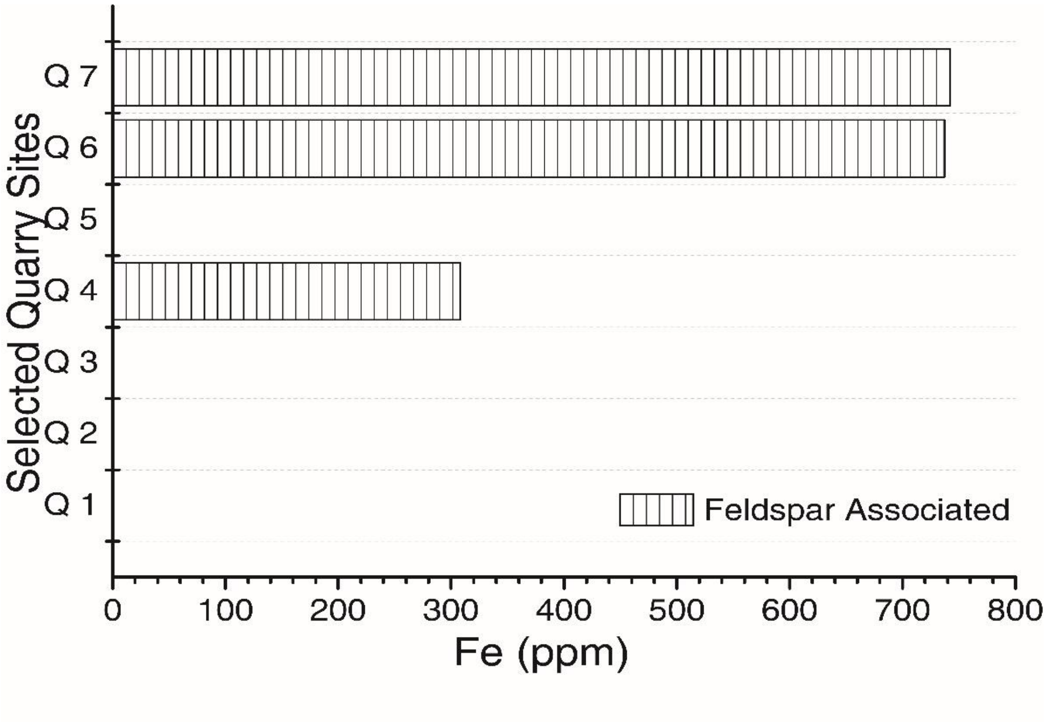

Figure 4.2.2.1-1: Fe concentration in feldspar-associated quartz

Appendix 3

Table 4.2.2.2: Al concentration in selected vein quartz deposits in Badulla

Site Name	**ppm**					
	Milky	**Rose**	**Smokey**	**Transparent**	**Mica**	**Feldspar**
Q 1	110			85		
	110			92		
Q 2	78	160				
	82	168				
Q 3	140	205	280	87	156	
	115	211	296	82	325	
Q 4	112		283	78		740
	100		259	83		743
Q 5	130	140			157	
	121	131			135	
Q 6		122	356			1715
		134	314			1738
Q 7			238		240	1959
			231		278	1905

Appendix 4

Table 4.2.2.3: Cr concentration in selected vein quartz deposits in Badulla

Site Name	**ppb**					
	Milky	**Rose**	**Smokey**	**Transparent**	**Mica**	**Feldspar**
Q 1	213			220		
	191			205		
Q 2	126	702				
	172	1784				
Q 3	184	1288	183	226	844	
	203	1369	196	232	891	
Q 4	105		272	252		868
	93		261	267		870
Q 5	240				931	
	198				896	
Q 6		960	808			1421
		689	790			
Q 7			293		911	1176
			250		934	

Appendix 5

Table 4.2.2.4: Mn concentration in selected vein quartz deposits in Badulla

Site Name	**ppb**					
	Milky	**Rose**	**Smokey**	**Transparent**	**Mica**	**Feldspar**
Q 1	189			209		
	168			190		
Q 2	180	495				
	156	315				
Q 3	350	644	390	201	693	
	188	596	331	180		
Q 4	240		363	204		18405
	233		347	213		16887
Q 5	242				865	
	221				831	
Q 6		696	380			518
		817	236			
Q 7			238		926	480
			221		1062	

Appendix 6

Table 4.2.2.5: Ni concentration in selected vein quartz deposits in Badulla

Site Name	ppb					
	Milky	Rose	Smokey	Transparent	Mica	Feldspar
Q 1	50			42		
	70			30		
Q 2	41	1580				
	52	1970				
Q 3	92	1172	820	32	817	
	103	1065	791	39		
Q 4	78		478	38		1175
	63		401	43		1661
Q 5	60				1161	
	56					
Q 6		1248	1296			860
		1201	1640			
Q 7			991		1709	807
			1026		1409	

Appendix 7

Table 4.6: Fe concentration in trailer contaminated quartz and clean quartz

Site Name	Fe (ppm) in Quartz	
	Clean	Trailer contaminated
Q 1	13	167
	15	168
Q 2	23	136
	18	135
Q 3	22	114
	24	121
Q 4	19	150
	22	147
Q 5	10	113
	11	121

Appendix 8

Prevention techniques of iron in quartz processing plant,

Crusher Feeder Bin

- Feeder bin should be thoroughly cleaned to remove any iron oxide crust until shining metal is exposed before feeding any new raw material. This has to be carried out by clean wire brush. Any oil or kerosene should not be used for cleaning.

Jaw crusher

- Crusher mouth should be thoroughly cleaned to remove any iron oxide crust until shining metal is exposed before feeding any new raw material. This is carried out by clean wire brush. Any oil or kerosene should not be used for cleaning.
- Alloy steel jaw plates should be used for crushing.
- Permanent full plate magnet should be fixed just after the delivery of output to the conveyer belt to capture the external iron particles. The strength of full plate magnet should exceed 12,000 gauss and the external width should be 30 mm excess to the width of the conveyor belt. Recommended brand name is Atlas Copco. Magnetic drum full with captured iron should be replaced by an extra drum and the former cleaned after removal. New magnet has to be in place before removing the existing magnetic drum while removal should be at every predetermined time interval with the maximum at 3 hrs and the minimum is 1 ½ hrs. Timing interval is valid for the above specified brand only. It should be ensured that no oil contamination takes place when the drum is replaced. Magnetic drum angular velocity and linear velocity of the convey belt should be synchronized at the processing stage. Gap between magnetic drum surface and conveyor belt surface should be optimized to ensure maximum external iron removal. Magnetic drum’s strength should be measured periodically and ensured that it should possess the necessary standard magnetic strength required for effective removal of external iron particles. If the magnetic strength is below the specified 10,000 gauss level, it should be replaced by a new one.

Conveyer Belt

- Full plate permanent magnets should be placed at every five-meter intervals above the flow level of the conveyer, at the optimized gap ensuring an extra sprocket at every location to remove iron particles. It is noted that all specified safeguard detailed out above should be observed wherever a magnet is located.
- Magnetic drums should also be placed near the point of the highest scattering of material for maximum capture of external iron particles.
- Ideally, the conveyer belt should be made of hard vulcanized rubber. In the existing setup, hence not endless belts, it is advised to cover belt joints properly with hard vulcanized rubber.

Roller Crusher

- Roller gaps should be optimized to minimize external iron contamination.
- Roller rotation speed should be optimized to minimize iron contamination.
- Roller gaps should be optimized to minimize the finer fraction (< 1 mm).

Vibrating Screen

- Material of screen mesh should be Ni free or less Ni material such as SUS 430, SUS 316 or SUS 304.
- Every 4 hour inspection of screen mesh is required to minimize over size and under size contamination.
- Feeding rate should be optimized for proper screening and reduce mesh damage.
- Permanent Full Plate Magnet should be fixed just after the delivery of output to the conveyer belt to capture the external iron particles. The strength of full plate magnet should exceed 12,000 gauss and the length should be 30 mm excess to the width of the conveyor belt.

Magnetic Separator

- Production flow should be optimized to capture the Fe material and Magnetic roller strength should be measured periodically and ensured that it should possess the necessary standard magnetic strength required for effective removal of external iron particles. If the magnetic strength is below the specified 10,000 gauss level, it should be replaced by a new one.

- Material and the thickness of rubber belt should not be changed in any situation, which may directly affect magnetism.

Centrifugal Pulveriizer

- Feeding rate should be optimized to build an inner layer and maximum output.
- Continuous feeding as well as recirculation of oversized material in same path with optimum speed should be considered.
- Exchange of spare parts with originals and on time with optimum condition is important.
- Removal of dust created inside the pulverizer should be considered to avoid contamination with products and the recommended power of the dust collector is 15 kW.

Swing Screen

- Material of screen mesh should be Ni free or less Ni material such as SUS 430, SUS 316 or SUS 304.
- An every 4 hour interval inspection of screen mesh is required to minimize over size and undersize contamination and to avoid mesh blocking and mesh damages.
- Feeding rate should be optimized for proper screening and reduce mesh damages

Tray type permanent Magnetic Separator

- Production flow should be optimized to do better magnetic separation
- Every hour magnets should have cleaned and replaced
- Minimum number of trays in the magnetic separator should be 12
- Magnetic tray strength should be measured periodically and ensured that it should possess the necessary standard magnetic strength required for effective removal of external iron particles