A study on the quartz veins found in Precambrian garnetiferous biotite schists around Sawantwadi area, Sindhudurg District of southern Maharashtra.

A Dissertation for

GEO 651 Dissertation

16 credits

Submitted in partial fulfilment of Master's Degree

M.Sc. In Applied Geology

by

DEEVYAM DEVILAS RAWAL

Seat No: 22P0450015

ABC ID: 315-038-999-491

PRN: 201805433

Under the supervision of

Dr. NICOLE SEQUEIRA

School of Earth, Ocean, and Atmospheric Science

GOA UNIVERSITY

May 2024

Examined by:

Seal of the School

DECLARATION BY STUDENT

I hereby declare that the data presented in this Dissertation report entitled, "A study on the quartz veins found in Precambrian garnetiferous biotite schists around Sawantwadi area, Sindhudurg District of southern Maharashtra." is based on the results of investigations carried out by me in the Applied Geology at the School of Earth, Ocean and Atmospheric Science, Goa University under the Supervision of Dr. Nicole Sequeira and the same has not been submitted elsewhere for the award of a degree or diploma by me.

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Deevyam D. Rawal

22P0450015

MSc in Applied Geology

School of Earth Ocean And Atmospheric Science

Date: 02/05/2024

Place: Goa University

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Dr. Nicole Sequeira

Assistant professor

Goa University

Date: 02.05.2024

Prof. Sanjeev C. Ghadi

Dean

School of Earth, Ocean and Atmospheric Science

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Date:

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Dean

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ABSTRACT

Quartz veins are invaluable in gaining insights into a regions structural, thermal and chemical history. The multiply deformed Precambrian supracrustal rocks comprising amphibolite facies garnetiferous biotite schists exposed in the Sawantwadi area, Sindhudurg District, Southern Maharashtra are intruded by several sets of quartz veins. This study concentrates on the field characteristics, microstructures, geothermobarometry and mineral chemistry to decipher the emplacement episodes, deformation mechanisms and mineralogical variations in these 10s of cm thick continuous and discontinuous quartz veins. The mesoscale structural features observed in the veins are En echelon fragments, upright to reclined open and closed folds, pinch and swell structure and crenulation. The most dominant set of veins in each outcrop is parallel to the penetrative foliation in the schists, although there are few cross-cutting veins also observed. The successive steeply dipping deformation fabrics in the schists striking N-S, E-W, NW and ENE, all contain quartz veins parallel to the foliation, indicating atleast 4 quartz vein emplacement episodes in the region. The veins are generally coarse grained, monomineralic in quartz but polymineralic veins containing hornblende segregations, plagioclase grains and calcite are also present in the area. Garnet-biotite thermometry and garnet-plagioclase-biotite-quartz barometry of the host rocks indicate a peak metamorphic temperature of 550°C and pressure of 9.6 kbar during deformation. The absence of high-temperature microstructures within the vein quartz and the presence of serrated boundaries, rare undulose extinction and occasional subgrain formation with subgrain boundaries perpendicular to vein elongation indicate that the veins are low-temperature intrusions. Fluid inclusions are ubiquitous. Comb structure present indicates that the veins are possibly related to extension during or subsequent to deformation fabric formation.

Chapter 1

Introduction

1.1 Introduction

Vein is a fracture or elongated cavity filled with the secondary minerals deposited from water rich fluid entering fracture. The term vein also used for melt filled with fracture such as small dyke and sills. Veins usually form in consolidated rock but there are indications of them forming in unconsolidated sediments (Passchier, 2005). Formation of veins is related to fractures as the veins in the rock grow inside the space created by the fracture formation hence the macroscopic shape of the vein formed is controlled by the fracture. A fracture is any planar or sub planar discontinuity that is very narrow in one dimension than other two and formed because of internal or external stress (Fossen, 2016). Fractures can be separated into shear fracture and extensional fracture.

Veins occurs in all types of rocks. The formation and growth of veins are closely linked to the movement of fluids within rock formations. The process involving fluid in this development is intricate, characterized by fluctuations in pressure. Periods of increasing pressure result in fracturing and the opening of veins, followed by a decrease in pressure during drainage, allowing for mineral deposition. Within an open system, materials found in veins can be carried from an external source through fracture networks or pore spaces, a process known as Advection. In a closed system, the minerals present in fractures are sourced from the surrounding wall rock through the dissolution and precipitation of minerals. Quartz and calcite are most common. Quartz is a common mineral found abundantly in the Earth`s crust, characterized by its crystalline structure and hardness. It belongs to the group of silicate minerals, composed of silicon dioxide (SiO2).

Four formation model mentioned in (Bons et al., 2012) are first model proposed mentions En echelons veins forms at the fringe of a single fracture . If the fracture propagates in all directions, fragmentation may occur at the propagating edge, where the fracture splits up in an array of fractures at an increasing angle to the “mother fracture” (Pollard et al., 1982; Foxford et al., 2000). Second model say the veins form as extensional fractures in a ductile shear zone (Rye and Bradbury, 1988; Ramsay and Huber, 1983; Laing, 2004). En echelon geometry is a resultant of maximum compressive stress making a high angle to the shear zone and veins formed at a same angle to the array. Alternatively, the shear zone is brittle, but the change of the stress field due to the shear-zone formation subsequently leads to extensional fractures at an angle to the shear zone (Rickard and Rixon, 1983). In the third model by (Olson and Pollard, 1991), fracture seeds are initially randomly oriented. As these fractures propagate, they increasingly interact with each other and develop into conjugate en-échelon arrays, where most shear is accommodated. The shear zone model and this model are therefore closely related, with the first having the veins as a result of the shear zone and the latter the shear zone as the result of the veins (Bons et al., 2012). In the fourth model, en-échelon veins can form by dilational kinking in a foliated rock (Roering, 1968) Once en-échelon arrays have developed, continuous deformation leads to a modification of the geometry. Interaction between individual veins commences once the ratio between spacing and vein length is small enough. Sigmoidal veins are special En echelon veins which are evolved. The term sigmoid refers to the Z and S shape of the separate segment in vein. Sigmoidal veins are result of simple shearing parallel to the vein array (Bons et al., 2012). Pinch and swell structure similar to boudins but does not separate in isolated fragments or boudins formed by the process of necking controlled by temperature, strain rate, viscosity contrast and well-developed foliation.

Dowling and Morrison (1989) had presented textural classification system based on the macroscopic attribute for these they studied quartz veins in over 200 gold deposits in Northern Queensland, Australia and defined eleven textural classes. These eleven classes were based on degree of crystallinity, grain size and form, density of crystal packing, preferential orientation of grain and the nature and intensity of deformation and recrystallisation. This was the first and only comprehensive classification of vein texture. J. R. Vearncombe proposed a new classification. New classification was based on the geometry of quartz addition this includes seven categories i.e., face controlled, displacement control, parallel controlled, radiating from one point, non-directional, modification and replacement.

In face controlled, crystal growth where sequential addition of quartz occurs on preferred face of crystal usually along c axis growing perpendicular to the vein wall. The term used by Cox and Etheridge (1983). Displacement control mineral growth by crack and seal mechanism involving microcracks opening and followed by sealing by crystalline material precipitated from solution by Ramsay (1980). Parallel controlled growth mimics the shape of the host rock surface. Radiating in which vein forming mineral grows from single point. Non-directional in this there no geometric control on the growth. Modification some fail to preserve their original texture due to alteration, recrystallisation and deformation.

If mineral in vein appears more or less equidimensional and randomly orientated the term blocky or sparry is used. Mineral may be elongate blocky with long axis perpendicular to fracture. The term elongate block was introduced by but (Fisher and Brantley, 1992). Elongate shape is obtained when crystal grows in open space and during repeated cracking. Mineral in vin even show fibrous growth due to lack of nucleation with relatively constant thickness across vein. Veins are also categorized in two types based on the crystallization of minerals i.e., Syntaxial and antitaxial. When mineral crystallize in veins from wall towards center are syntaxial veins but (Fisher and Brantley, 1992) work mentions occasionally crystal can grow from one side of the wall towards the other and if mineral crystallize from center toward wall, then Antiaxial term is used. In syntaxial veins there are very few inclusions. Syntaxial vein formed due to single or repetitive fracturing. In latter case, space is added during fracturing and cracking event is partly or fully filled as crystal continues to grow this process is termed as healing. The process of repetitive cracking and filling is known as crack and seal mechanism introduced by Ramsay (1980). Syntaxial veins can form by crack and seal mechanism (Ramsay, 1980; Urai et al., 1991) Stretching veins can form due to repeated fracturing within or outside vein material. In Antiaxial veins median zone is well preserve which is not the case in syntaxial veins. If antitaxial vein gets sandwiched between syntaxial vein then the vein is called as composite vein. Ramsay and Huber (1983) mentioned veins that lies at a high angle to opening direction are known as tensional gash however veins can also form at a small angle to the opening direction in that case they are referred as shear veins.

Quartz and calcite veins are most occur most commonly. Veins can unravel the deformation history by its structure and the crosscutting relationship. Shape of the vein is useful in determining shear sense. Veins hosting economic mineral deposits are exploited all over the world

1.2 Aim and Objectives

Aim

To study the variations in meso and micro scale structures in quartz veins in biotite schists around Sawantwadi area, Sindhudurg District of Southern Maharashtra and decipher their tectonic evolution

Objectives

- To characterize the field structures of the quartz veins in the study area.
- To identify the microstructures and constrain the mineral chemistry associated with the quartz veins through petrographic analysis.
- To decipher if the quartz veins influenced the growth of mineral phases in the host rock

- To try to infer the correlation between the origin of the quartz veins and the deformation in the country rock

1.3 Physiography

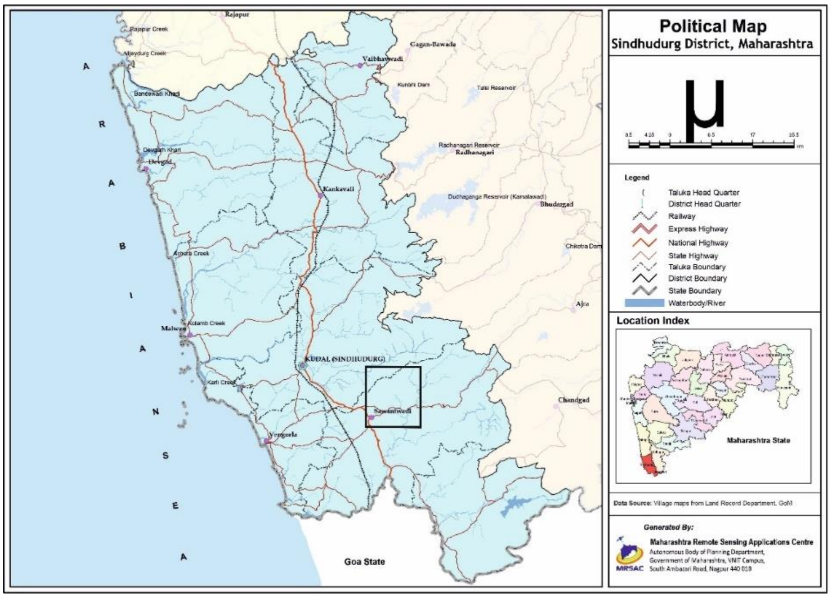


Figure 1 Political map of Sindhudurg district Maharashtra (Src: Maharashtra Remote Sensing Application Centre)

The state of Maharashtra is situated in the west central part of India. It occupies an area of about 3,07, 762 km. It is surrounded by the Gujarat, Madhya Pradesh, Andhra Pradesh and Karnataka and Goa in the North, Northeast, Southeast and Southwest respectively and Arabian sea on the Western border of the state.

Sindhudurg district is situated in the Konkan region of Maharashtra State, covering an area of 5207 sq.km. It falls within Survey of India degree sheets 47H, 48 E, and 48 I, positioned between latitudes 15°37’ and 16° 40’ north, and longitudes 73° 19’ and 74° 13’ east. The district is bordered to the north by Sindhudurg district, to the west by the Arabian Sea, to the east by Kolhapur district, and to the south by Goa State and Belgaum district of Karnataka State. National Highway 66 traverses the district connecting it to Goa. Its well-established road and rail connections with Goa and Mumbai. Encompassing 5207 sq. km geographically, approximately 386.43 sq.km. is forested, while the cultivable area spans 3222 sq. km with a net sown area of 1522 sq. km. Sindhudurg has famous tourist attraction includes Malvan fort and water sports.

1.4 Study area

The study area is situated on the west coast of India. The location is within 70-90km from Goa University. Sawantwadi is the neighbouring town to the study area. Kudal in the north and Banda in south are the two major neighbouring town. Study area is well connected by road network. Study area fall in western ghats range. North-south trending Insurli ghat encountered along the road. In some areas are dense forest is seen. The main activity in the study area is farming. Large agricultural land and cash crop plantations are commonly observed. The study area falls under latitude 15°54'N and 16°2'N and longitude between 73°50'E and 73°54' E respectively. The present study area falls in Sindhudurg District of Southern Maharashtra (parts 47H/16/SE & 48E/13) that forms the South-Western tip of the Maharashtra State and has geological continuity with the states of Goa and Karnataka. Study area comprised of metapellites and granitoid rocks. This metapellites include biotite schist, biotite quartz schist and amphibolite schist.

1.5 Methodology

Methodology was divided into two parts field study and the laboratory work. Field study consist of detailed mapping of the study area. Collecting structural data, observing mesoscale structures shown by the quartz veins and its relations. At primary stage, outcrops were selected around study area using google earth pro software. Structural data was recorded using clinometer compass. Proper sampling was done. A sample should be a representative of the area. Rock samples were collected using the jackhammer and the geological hammer. Each sample named according to the study area and stored in sample bag. During sampling weathered and the eroded surface of the rock was discarded and the fresh sample was collected. Collected structural data was entered in excel spreadsheet to use it for creating stereographic projection using georient tool for better understanding.

Laboratory work was divided into thin section preparation, petrography, electron microprobe analysis and zircon separation. For laboratory work, all the equipment which were available in the Hard Rock Laboratory, Applied Geology at the School of Earth, Ocean and Atmospheric Science, Goa University was utilised. To prepare thin section, collected rock samples were cut to appropriate sizes using rock cutting machine. Rock sample must be cut orthogonal to foliation and parallel to lineation ((Spry, 1969) (Blenkinsop, 2002.) (Vernon, 2004) (Passchier, 2005)). Polished using different grades of carborundum powder starting with 80 grade till 1200 grade powder. Glass slide also must be polished before sticking rock sample using adhesive. To cut access rock portion, rock cutting and grinding machine was used. Final step before slide is ready to observe is to grind slide again till the minerals in the slide shows their correct optical properties under the petrological microscope. Samples were sent for silicate mineral chemistry to the National EPMA Facility, Department of Earth Sciences, IIT Bombay, Mumbai, Maharashtra, India. To carry out EPMA analysis of Rock thin section thickness of slide must be 30 micron. Analysed data in converted into excel file for further calculation. . To carry out EPMA analysis of Rock thin section thickness of slide must be 30 micron. Analysed data in converted into excel file for further calculation. Collected field data was used to produce rose diagrams and stereographic projection using stereonet, CorelDraw software was used to highlight images. Software named PTQuick used to analyse pressure and temperature condition.

Chapter 2

Literature review

2.1 **Geology of Dharwar craton**

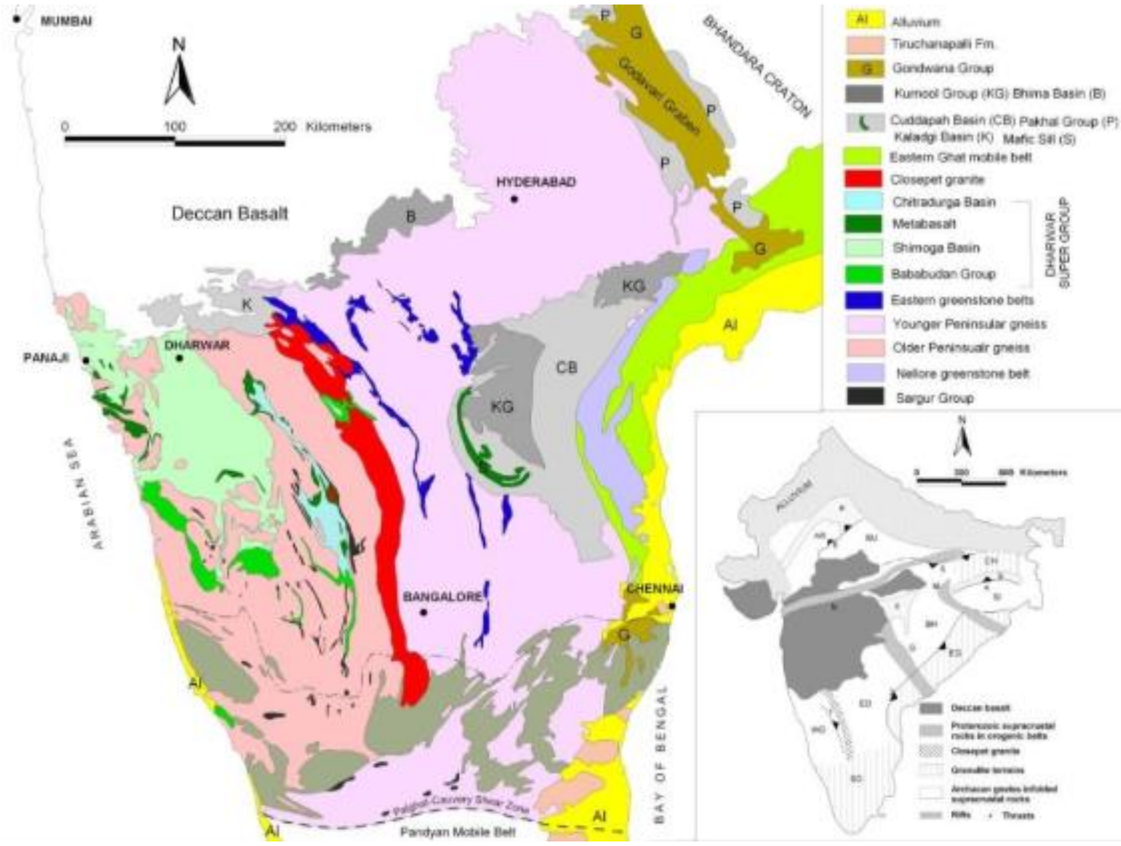


Figure 2 Geological map of Dharwar Craton (adapted from Bongale, P., & Kshirsagar, M.A. (2015).)

The Indian Peninsular Shield is a large and historic area. 4 billion years ago during the Precambrian Period, when the Earth was still growing and fresh land was being formed. It was during this period that the vast landmass known as the Indian Shield began to take shape. The Indian Shield has been molded over millions of years by a complicated history of sedimentation, magmatism, and tectonic action. As a result, a wide variety of mineral deposits and rock types have formed, along with old geological formations including cratons, mobile belts, and orogenic belts. The complicated geology of the Shield is primarily made up of metamorphic rocks including gneiss, schist, and granite. It is estimated that the Archean Period, from 2.5 billion to 4 billion years ago, is when these rocks formed. The area has seen numerous episodes of deformation, metamorphism, and igneous activity throughout its history, giving rise to a variety of rock types and mineral deposits. The development of the Indian subcontinent's natural resources and geology have been significantly influenced by these old geological formations.

In Southern India, the Dharwar Craton occupies an area of 4.5 lakh square kilometers. Granite-greenstone landscape, with rocks older than 2500 million years, has been designated. The Proterozoic Kaladgi and Bhima basins, the Archean Karimnagar Granulite Belt (KGB), the Neoproterozoic Eastern Ghat Mobile Belt (EGMB), and the Arabian Sea, which divides Madagascar and India, encircle the northern portion of the Cretaceous Deccan trap (Ramakrishnan & Vaiyanadhan, 2010). The Dharwar Craton is composed of a number of tectonic-metamorphic units, including: (a) later shear belts; (b) gneissic complex; (c) newer granites; (d) granulite terrain; and (e) high to low-grade supra-crustal belts (Dhruba Mukhopadhyay., 1986).

The oldest rock found in the Western Dharwar Craton is the tonalite trondhjemite granodiorite (TTG) gneisses, as was previously mentioned in relation to the sections of the Dharwar Cratons and Shear zones. The Gorur Gneisses are the TTGs that are present here. According to some theories, the formation of the Gorur Gneisses resulted from partial melting of basaltic rocks at the crust-mantle boundary or in the lower crust. These rocks can currently be found close to the Precambrian tectonics' volcanic arcs, which are associated with subduction zones. The presence of extremely high-pressure minerals in the TTGs indicates that the crust's overburden pressure was high, which led to the formation of these minerals. Compared to the Central Dharwar Craton and Eastern Dharwar Craton, the Western Dharwar Craton has more TTGs. They differ significantly from those in the eastern and central blocks. While the TTG partially melt in Eastern Dharwar Craton and Central Dharwar Craton, they form circular to elliptical domes with widely spaced shears in Western Dharwar Craton. The shears in Eastern Dharwar Craton and Central Dharwar Craton are closed spaced and range in depth from shallow to steep. Stratigraphically speaking, the TTG, often referred to as Peninsular Gneiss, are thought to be younger than the Gorur gneiss. These TTGs range in age from 3.45 to 3.22 Ga in Western Dharwar Craton; the transitional TTG in Central Dharwar Craton is 3.3-3.0 Ga old, and in Eastern Dharwar Craton it is 2.7-2.5 Ga old. The age of the TTGs in the Western Dharwar Craton close to Karwar and Amboli is 3.6 Ga.

The shear zone number is highest in the Western Dharwar Craton and decreases towards the east. From a structural perspective, the TTG gneisses and plutons (K-rich), which comprise the dome, are what make up the basin patterns and dome in Western Dharwar Craton. The belts of greenstone are located in the basins in between the domes. Among the rare signs of the sagduction process, or vertical tectonics, are these dome and basin patterns. Regional metamorphism is thought to have occurred along the whole Dharwar Craton block; however, the Western Dharwar Craton is different from the others due to its higher pressure. It is claimed to have experienced Barrovian-type regional metamorphism.

The Older Sargur Group (3.1-3.3 Ga) and the Younger Dharwar Supergroup (2.6-2.8 Ga) comprise the Volcanic Sedimentary Greenstone Sequences. Subordinate basaltic to felsic rocks, interlayered shallow shelf assemblages, and komatiitic to high Mg basaltic volcanic rocks are the main features of the Sargur Group. High deformation has resulted from the metamorphism of several sedimentary strata in this area. There is tectonic contact between the basement gneisses and the Sargur Group. The Dharwar Supergroup, also known as the Younger Greenstone sequence, is further subdivided into the Upper Chitradurga and Lower Bababudan groups. Here, the occurrence of conglomerates indicates an angular nonconformity. These conglomerates, which are composed of quartz pebble conglomerates (QPC), are referred to as the Kartikere Conglomerate. The Bababudan Group rests on the Kartikere Conglomerate. Low-grade volcano sedimentary greenstone sequences can be found in the Bababudan Group (2.91-2.72 Ga). They come into unpleasant touch with the basement and supracrustal rocks. The quartzites and conglomerates found there are thought to have originated in riverine settings. The cross beddings found in the quartzites imply that a shallow maritime environment of deposition.

The younger Dharwar-Shimoga band to the west and the Chitradurga Gadag belt to the east make up the Upper Chitradurga group. There are two age groups that are dominantly older—3.6-3.36 Ga and younger—2.6 Ga in the Goa schist belt, which is thought to be the northern extension of the Dharwar Shimoga belt, and the Gadag greenstone belt, which is the northern extension of the Chitradurga greenstone belt. An oligomictic conglomerate leads the lithological sequence in this area, which is then followed by thick Banded Iron Formations (BIFs), carbonate, greywacke-argillite, carbonaceous phyllites, and intermediate to felsic volcanic (pyroclastic) rocks. The SW has a shallow water sequence (oligomictic conglomerate quartzite-carbonates), while the SW and W are thought to have steadily deeper water facies (greywacke-argillite-carbonaceous shale-BIFs) that lead to the NE and a stable shelf habitat. There are two subgroups within the Chitradurga group. The Vanivilas subgroup is older, while the Ranibennur subgroup is younger. The Proterozoic mafic dykes, Charnokites, and younger granites are older than the Chitradurga group.

The greenstone sequences in the Central block include the Kushtagi Hungund belt, Penukonda Ramagiri Penakacherla, and Sandur. Compared to the Western Dharwar Craton, the Central Dharwar Craton has a smaller belt. Together with inferior sediments, they are primarily composed of mafic and intermediate to felsic volcanic. Mafic rocks make up a larger portion of them than sedimentary rocks. This suggests that the environment has undergone alteration. We still don't know how abrupt environmental shifts occurred so close to one another. The alteration in the environment also implies that the current greenstone belts have undergone distinct ages and stages of evolution. They exhibit tectonic contact with strata that are 2.7 Ga older in the vicinity.

The Central and Eastern Dharwar cratons have more voluminous lithologies of the calc-alkaline to potassic plutons than the Western Dharwar craton. These served as the heat engine and primary forces of sagduction tectonics, or granite-greenstone tectonics. They were crucial for the mineralization of gold as well. Granite, granodiorite, quartz-monzonite, and monzogranite are among the high potassic granitoids that make up the plutons of the Western Dharwar Craton. They are also epidote-bearing. They intrude the TTG-greenstone associations in the west during two significant crustal reworking events, 2.62 2.6 Ga and 3.0 Ga. They introduced several fluids rich in precious metals, including gold, when they were buried in the crust. when they encroached upon the greenstone belts, which are supracrustal rocks. The liquids moved into the shear zones and fissures in the greenstone. From the fluids that we mine, the valuable metals precipitate out of them. The fluids were produced when the greenstones were formed and the granitoid was inserted into the crust.

In the TTG greenstone of Western Dharwar Craton, these granitoid intrusions happened during two significant crustal episodes. They were further distorted in Phase 1 at 3.0 Ga, and we combined them with TTG gneiss. They were more deformed because of their earlier intrusion. Certain potassic plutons developed gneissic rock-like bandings, giving them a gneisses-like appearance. The major intrusion phase is thought to have occurred approximately 2.6 Ga, or phase 2. In the Western Dharwar Craton, they originated as multiple distinct plutons. The TTGs were invaded by granitic plutons such as Arsikere, Banavara, Hasdurga, and Dudhsagar. It is evident that the granites are younger than the greenstones of J.N. Kote and Chitradurga since they are intruding on the greenstones. The granitoid emplacement in Central Dharwar Craton and Eastern Dharwar Craton is associated with the regional shear zones. Because there are so many of these shear zones in Eastern Dharwar Craton, there are easy routes for granites to be deposited. Potassic pluton has been heavily deposited throughout the late Neo Archean. As a result, the Precambrian was split into the Archean and Proterozoic.

It is well known that the crust thickens and becomes more stable due to the potassic granite. Numerous processes take place continuously when granites are deposited through shear zones. Because the granitoid need space for formation, the shear zones or faults provide them with an upward path and enable them to be deposited near the surface. Because they are in melts, or the molten state, when they are positioned, they can withstand greater strain when they bend ductilely. More shear zones may arise as a result of these strains being accommodated along the plutons, creating a feedback process. The most significant granites in Dharwar are the Closepet granites. The plutons are home to Mafic Magmatic Enclaves (MME) and syn-plutonic mafic to intermediate dykes, which exhibit interaction, mixing, and mingling with the host granitoid. These enclaves provide us with a brief overview of the plutonic rocks' magma chamber. The granitoid's -Pb zircon age values are late Neoarchean, 2.57-2.51 Ga.

2.2 Geology of study area

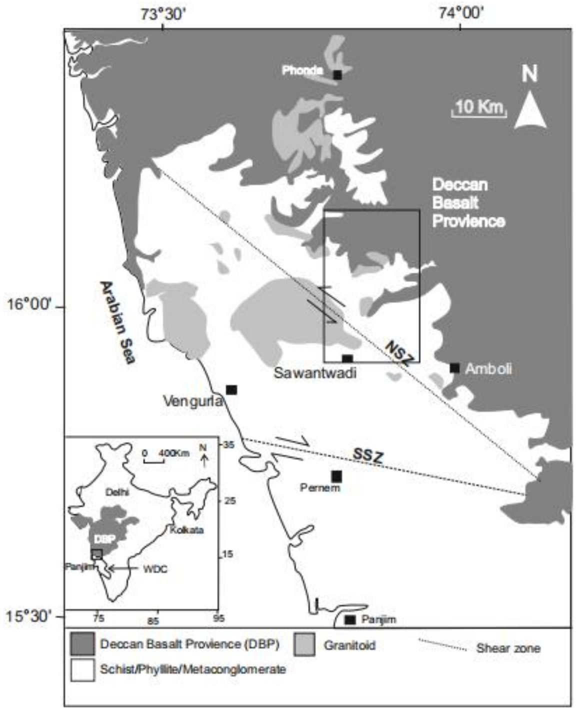


Figure 3 Generalized geological map of Pernem (Goa)-Phonda (Maharashtra) corridor modified after Rekha and Bhattacharya (2014) . Black Box indicates study area shown in (figure 4).

Sindhudurg District forms a part of Konkan Region. The rocks of Sindhudurg District were initially mapped and labelled as the "Older Metamorphic Series" by Wilkinson in 1871. Foote, in 1876, was the first to document the presence of the "Gneissic Series with granitic intrusion" after conducting field studies following Wilkinson's work. Iyer (1939) identified both unmetamorphosed and metamorphosed Kaladgi Series in all the pre-Trappean rocks of South Konkan, Maharashtra. Kelkar (1956) distinguished two groups of Archean metamorphic rocks with a thrust contact between them; Group I comprised granite, gneiss, quartzite, mica schist, garnet, staurolite, kyanite, biotite, hornblende granulites, and coastal rocks like crushed conglomerate, phyllites, and ferruginous quartzite, while Group II was formed mainly of schists. The metamorphic rocks in Sindhudurg District were classified as the Banda Group with the Castle Rock Band, suggesting their equivalence to the middle and upper divisions of the Dharwar Supergroup by Ghodke (1983). Subsequently, Naqvi S.M. and Rogers (1987) proposed that the schists along the Western coast of India and Goa could be extensions of Karwar, intruded by South Kanara Batholiths (2700 Ma).

(S. S. Ghodke, 1970) have identified that most folds in the study area are isoclinal and also asymmetrical folds are observed. They have also mentioned that at some places tight folds have oppressed limbs to more open folds, with occasional detached limbs. (Rekha et al., 2014) also mentioned that biotite schists show several generations of folds and tectonic fabrics whereas granitoid rock possess single fabric. They identified two shear zones with protomylonite bands within the corridor. NNW trending Northern shear zone (NSZ)which can be traced 100km from south of Mugane to north of Bhedshi. As moving towards NSZ folds becomes tighter with curved hinge.(Rekha et al., 2014) also mentioned that there is sinistral shear sense near NSZ. Second shear being Southern Shear zone (SSZ) which can be traced for 50km in the north Pernem to south Bhedshi. Z-shaped north-vergent intrafolial folds on quartz veins. Dextral shear sense seen in quartz vein near SSZ is also mentioned. (Dashputre et al., 2019) has shown three phases of progressive deformation events in the area where D1 has axial trace of which is roughly N-S, D2 with an axial trace of E-W and D3 with axial trace of NE-SW on the regional scale.

Chapter 3

Field characteristics and Structural analysis

3.1 **Field characteristics and Structural analysis**

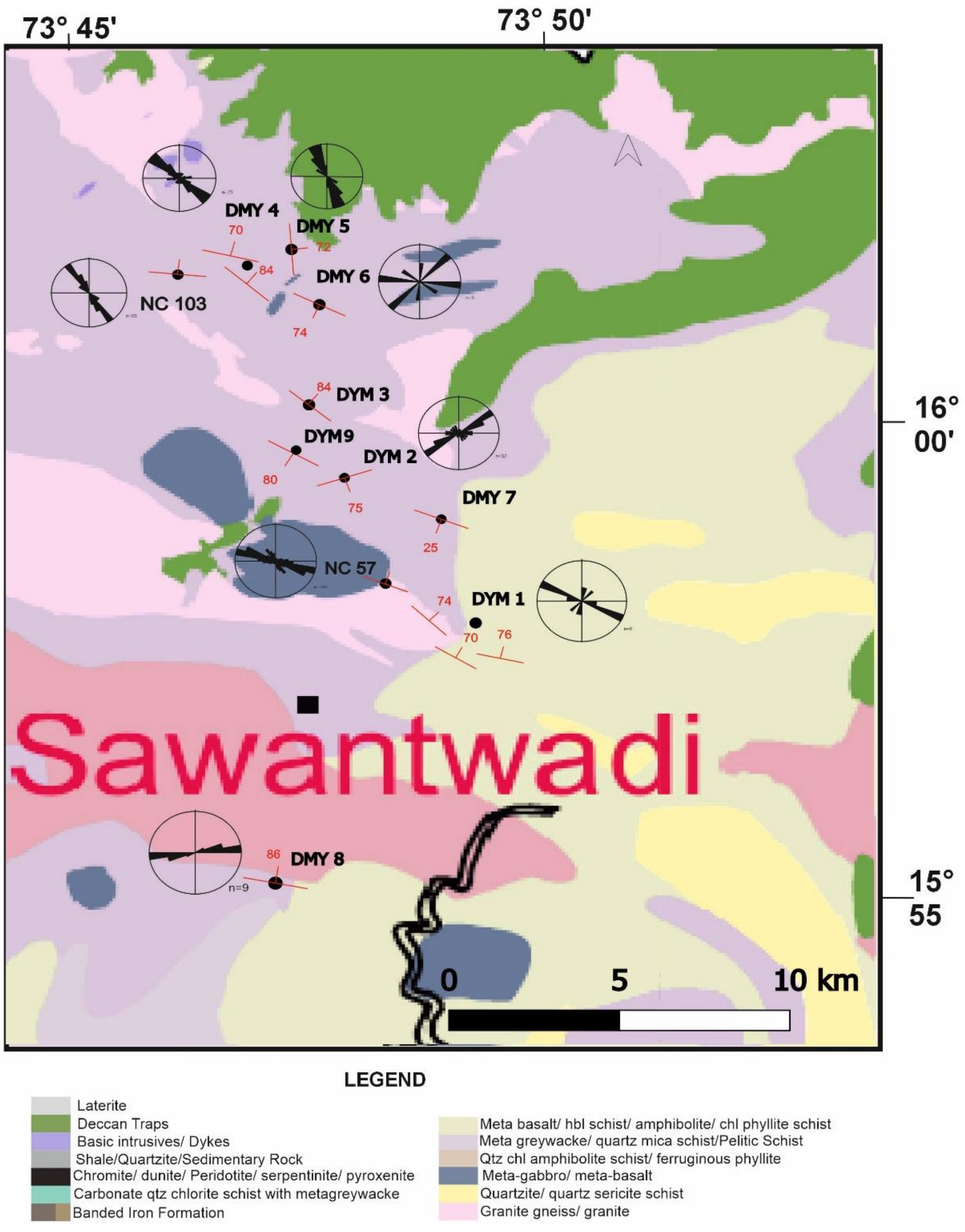


Figure 4 Lithological map of the study area modified after GSI(2021) District Resource map of Sindhudurg, Keyed to the map are penetrative foliations in each outcrop and rose diagram plots of the orientation of steep quartz veins.

The study area comprises of schists which includes biotite schist, quartz biotite schist present with or without garnets, amphibolite schist and granitoids with quartz veins. Biotite schists are fine to medium grade rocks showing lepidoblastic schistosity defined by alignment of biotite mineral which imparts foliation to the rock. The garnets in the rock are in millimeter size grains and can be identified by unaided eye reddish colored grains showing size variation. Euhedral in shape. Quartz veins observed in rock formed due to precipitation of silica in the fracture or cavities formed during deformation event. The quartz veins in the rocks varies in size from few millimeters to centimeters showing various mesoscale structure. Most of the quartz vein are present in study area are parallel to the foliation.

Figure 5 Field photograph of the E-W striking garnetiferous biotite schist present in study area.

Following foliation identified in the rocks present in the study area:

1. Steeply dipping N-S foliation
2. Steeply dipping E-W foliation
3. Steeply dipping N130° foliation
4. Steeply dipping N65° foliation

Study area has quartz veins, sheath folds and box work structure. Most of the quartz veins are parallel to sub parallel to the foliation of the outcrop. Quartz veins in the study area shows folding, pinch and swell structure, crenulation and En echelon vein. Most of the outcrops chosen for the study show quartz vein parallel to sub parallel to foliation of the study area. Most of the outcrops chosen for study had single penetrative foliation.

Steeply dipping N-S foliation was observed trend varying from N360°-N20° and dip amount was 60°-70 due east. Foliation is seen in the northern part of the study area. The lithology consists of garnet bearing quartz mica schist. Quartz veins present in the area were parallel to sub parallel to the penetrative foliation.

Steeply dipping E-W foliation was observed in outcrops present between Gothos and Kunkeri villages having trends between N90°-N120° with a varying deep amount towards north. Dominant lithology in the area is garnet bearing medium grained quartz biotite schist. Quartz veins in the area showing En echelon, pinch and swell structure, folds and crenulation in the veins trending in NW direction. Veins showing pinch and swell structure trending in N100°-N150°. Quartz vein trending N110°-N130° had crosscut E-W foliation in study area. Some quartz veins trending E-W in cross cut sheath folds in the study area. One of the En echelon vein is observed curving towards north in NC-57.

Steeply dipping N130° foliation was the most dominant foliation observed in many outcrops. Most of the quartz veins in the study area show pinch and swell structure in this trend. Most of the veins lie parallel to sub parallel to this foliation and were steeply dipping or vertical. . Steeply dipping N65° foliation was observed in the Sutarwadi, Ambegaon outcrop where most of the quartz veins were trending in N65°-N70° and dipping steeply. Amphibolite layer trending in N60° is crosscutting E-W trending vein in the outcrop.

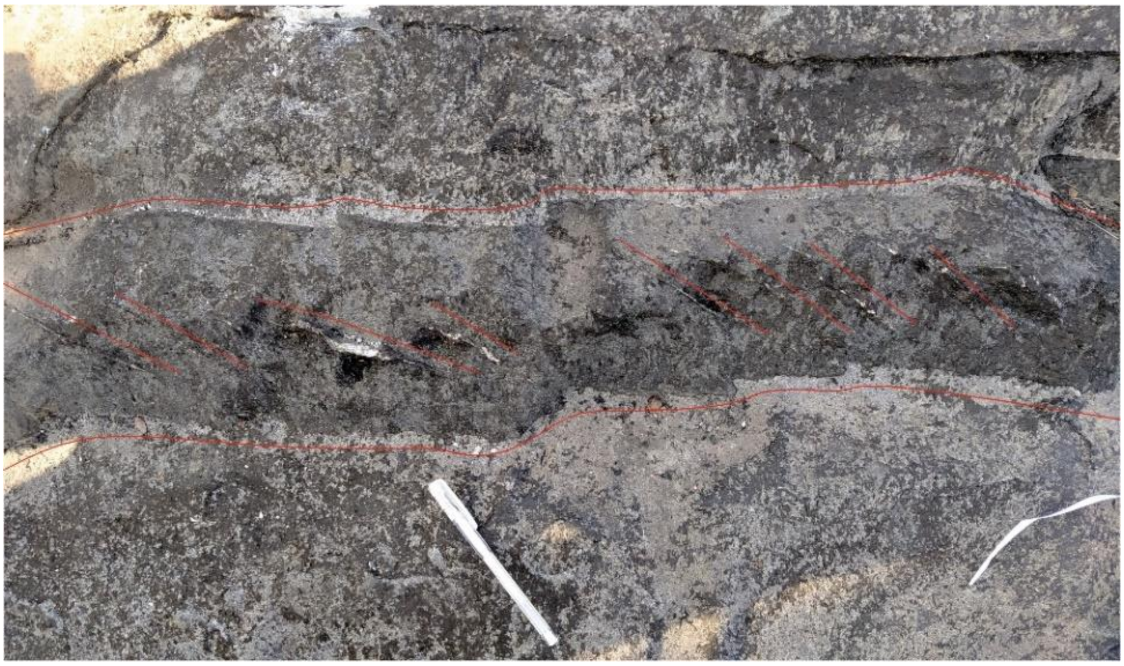


Figure 6 En echelon quartz vein array seen restricted in calc-silicate layer within biotite schist in location NC103

Figure 7 Crenulated vein folded with axial plain N160.

Figure 8 Vein trending in E-W direction crosscut by metamorphosed mafic dyke trending in N60

Figure 9 Boudins trending in N60

Figure 10 Field photograph showing dextral shear sense in a calcic layer.

Figure 11 Field photograph showing garnet size variation(arrow pointing toward decrease in size) besides quartz lens

Figure 12 field photograph showing folding in quartz veins having axial plane N110 which is intrafolial to N65.

Figure 13 Field photograph showing fold in the quartz vein

Figure 14 Field photograph showing quartz vein crosscutting shear at NC 57

Figure 15 Field photograph showing En echelon vein curving toward north in NC 57

Figure 16 Field photograph showing folding in quartz vein with axial plane in E-W direction.

Figure 17 Field photograph showing crenulated vein in E-W direction.

Figure 18 Field photograph showing boudin trending in N130.

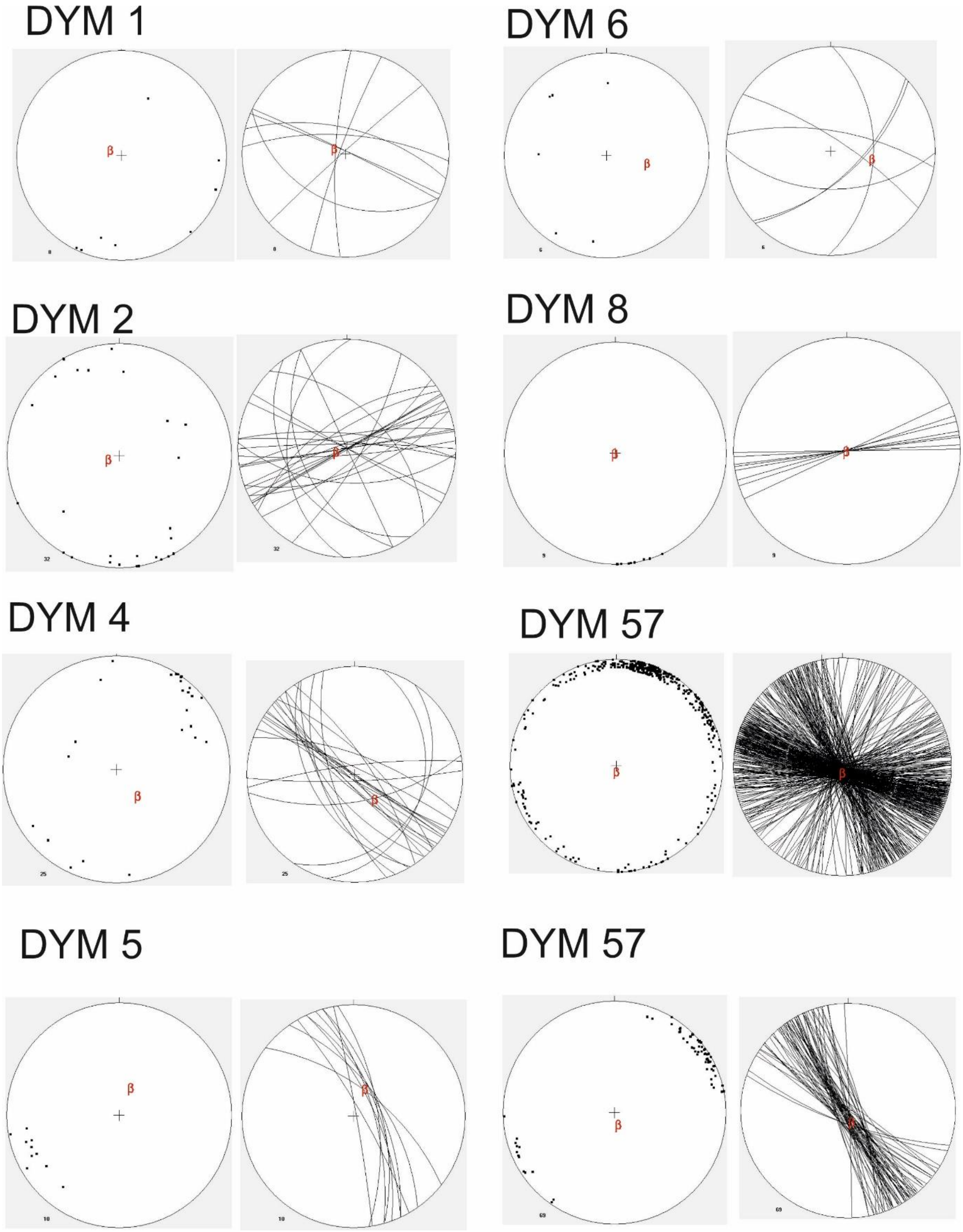
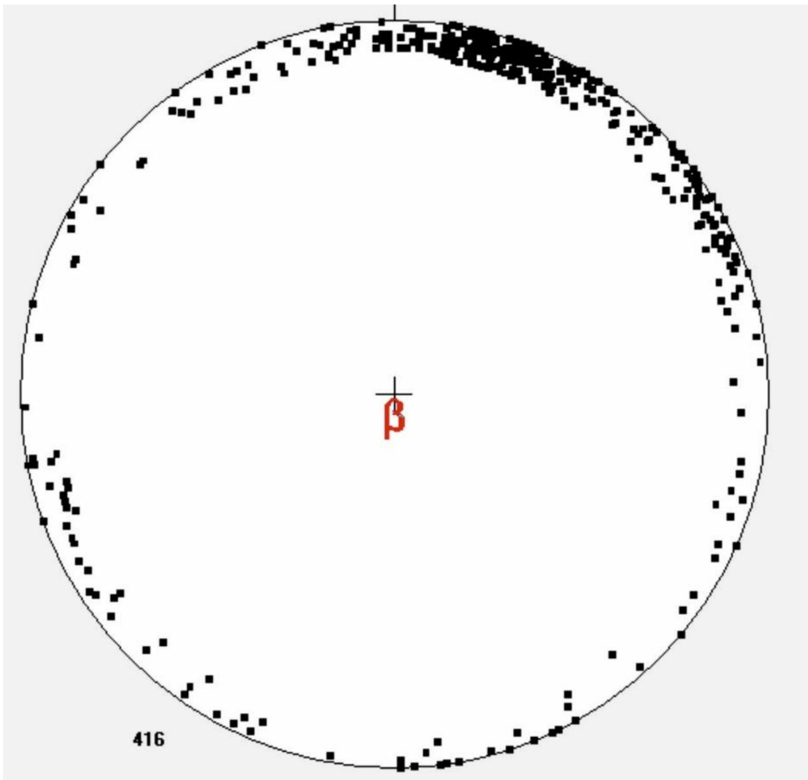
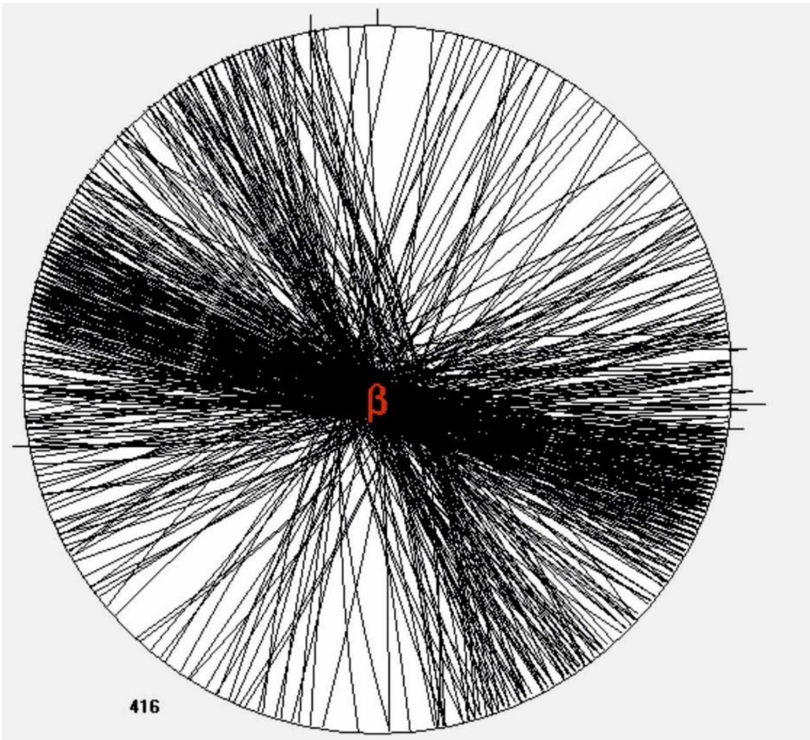


Figure 19 Stereographic projection of poles and strike for quartz veins in each study area



(a)



(b)

Figure 20 stereographic plots (a) and (b) of poles and strike data for steep quartz veins

CHAPTER 4

Petrography and Mineral chemistry

4.1 Petrography and Mineral Chemistry

Petrography is the study of rock in thin section by means of petrologic microscope with systematic classification and precise description of rock. A texture of metamorphic rocks reflects the combined processes of nucleation crystal growth and diffusion matter(Danial and Spear, 1999). As rock heat and cools their minerals and structures progressively changes and so the main aim of studying microstructure of metamorphic rock is trying to infer the history of these changes (Vernon, 2018). Nikon E200 petrographic microscopes available in Applied geology laboratory of Goa University, Taligao were used for analysis. The study area comprises of biotite schist with or without garnet which is exposed in Sawantwadi, Sindhudurg district of Southern Maharashtra, India. Granitoid rocks also present in area which are characterized by the single tectonic fabric (Rekha, 2014). The rock is layered, biotite schist- amphibolite and intercalated calcic layer is present along the foliation. The biotite schist is composed of biotite + quartz ± Garnet ± plagioclase(sausseritized) ± chlorite ± calcite and amphibolite composed of hornblende + diopside ± garnet + plagioclase(sausseritized) + scapolite ± calcite + iron oxide. Biotite is a dominant mineral that defines the tectonic fabric in biotite schist.

Mineralogy of the Matrix

Biotite Schist with or without garnet

Minerals in the thin section shows fine to medium grains sizes. The most abundant minerals in the rock are Biotite, Hornblende, Quartz and Garnet. The biotite schist is composed of biotite + quartz ± Garnet ± plagioclase (sausseritized). Biotite is flaky mineral defines the foliation. Biotite is elongated, fine to medium size grain, subhedral in shape shows pleochroism in yellow to brown shades and has straight extinction which defines lepidoblastic schistosity in the rock representing deformation event. In biotite rich layer horizontal to slightly inclined dark region or zones are present like and intrusion of some fluid. Along these zones crystallization of colourless mineral is seen with anhedral shape which shows first order grey colours. Biotite grains which are present in contact with this zone shows slightly darker colouration at the borders the other grains. Biotite grains shows kink banding (Figure 23). Kinking is observed when slip on a single plane is inadequate to maintain homogeneous deformation. The grain sharply bends and deformation localized into kink bands which enables shortening of the grain to continue. Kink band define as the part that undergoes rotation with respect to unkinked part of the grain. Biotite grains forms a cluster to form a porphyroblasts. Quartz grains in the present matrix has fine to medium grain size which colourless to yellowish, non-pleochroic, xenoblastic texture i.e., anhedral in shape, low relief having 1^{st} order grey colour and undulose extinction. Undulose extinction form as a result of dislocation which forms and migrate so the portion of crystal lattice. This migration and reorientation crystal as the polarising position of the mineral depend upon the crystallographic orientation. Dislocations enhances the mineral capacity to accommodate stress. Quartz grains in the rock shows sutured, serrated, sinusoidal and straight boundaries. (Stipp et al 2002) has shown that sutured and serrated are evidences of recrystallization. Grain boundary migration refers to the development of new boundaries. In grain boundary migration the atoms in a grain with the higher strain energy migrate by diffusion and neighbouring grain with lower strain energy which is also called as bulging (Winter, Principles of Igneous and Metamorphic Petrology, 2013). Bulging can be seen in the thin section. Garnet porphyroblasts are very common in the area. Porphyroblasts are most useful for determining deformation history and are more resistant to deformation. Porphyroblasts can be used as shear sense indicator. Garnets of various sizes are observed. Garnets present in the biotite layer shows idioblastic- subidioblastic texture i.e., euhedral with well define grain boundaries contains very few inclusions of quartz, plagioclase and biotite. Garnet grains are wrapped by biotite grains. Garnet mineral growth can be further divided into four types on the basis of timing of growth during a deformation event i.e., pre-kinematic, syn-kinematic, interkinematic and post-kinematics. Pre-kinematic refers to formations of porphyroblasts before deformation event. Syn-kinematics refers to formation of porphyroblasts during deformation and post-kinematics refer formation of garnet after deformation event. Inter-kinematics is post-kinematic to one event and pre-kinematic to another. Garnets in biotite schist are syn-kinematic (Figure 20). Garnet with biotite inclusions also seen. In domain of progressive deformation, these biotite inclusion in garnet grains can be used as part of previous foliation in such event garnet will be precursor to the deformation event and will be known as interkinematic garnet. Biotite grains present with the chlorite mineral grain layer shows different alignment the interkinetic chlorite mineral grains where chlorite grain boundaries are serrated and sinusoidal. Reduction in chlorite grain size and number of chlorite grains are observed towards biotite garnet rich layer. Plagioclase grains are showing alteration which is known as sausseritized. Plagioclase rich domain present near the contact of Chlorite layer and biotite layer. Throughout the thin section the sausseritized plagioclase are observed. In chlorite rich layer very little and small quartz grins are seen but the number and size of quartz increases in biotite dominant layers.

Amphibolite schist

Amphibolite schists composed of hornblende + diopside ± garnet + plagioclase(sausseritized) + scapolite ± calcite + iron oxide. Hornblende is prismatic, fine to medium pleochroic showing shades of green and yellow, with 2nd order colour with oblique extinction. Hornblende mineral grains does not show very well defined nematoblastic schistosity. Plagioclase grains present in the rock are sausseritized (Figure 20) whereas few grains which are present in near quartz vein shows no sign of alteration with lamellar twinning. Multiple lamellar twinning is rarely seen in few plagioclase grains. Garnet grains are identified based on pink colour, high relief, highly fractured and isotropic. Garnet contains inclusion of other minerals like quartz, plagioclase, hornblende and diopside. Amphibolite layer contains skeletal garnets. Skeletal garnets formed due to limited of mobility of ions. At greenschist and lower amphibolite facies condition, aluminium ions being less mobile than the other ions unless the pH is extremely low or high or if salinity is extremely high. Skeletal garnets(Figure 22). form in the Al poor domains. Theses garnets are surrounded by the diopside mineral in the amphibolite layer. Garnets in the biotite layer are euhedral in shape but in amphibolite layer they are skeletal. Garnet grains in amphibolite layer are surrounded by the diopside mineral their boundary is sutured and serrated. Garnet in amphibolite layers is more fractured. Garnet in amphibolite layers contains inclusion of opaque mineral. Intruded by fracture filled with the psuedotachilite. Scapolite grains are also present which forms due to alteration of plagioclase. Scapolite grains are colourless doesn't show any distinct cleavage, shows 2nd order birefringence colour. Diopside pale green colour pleochroic and 2nd order extinction colour. Hornblende mineral does not show any alignment and are randomly oriented. Hornblende shows decussate texture in thin section.

Mineralogy of Veins

Veins are the fracture filled by the secondary mineralisation. Most common are quartz and calcite veins. Precious metal deposits occur along these veins example gold deposits. Quartz, calcite, opaque mineral, and polymineralic veins are seen in the thin section.

Quartz veins

Quartz veins present in between biotite schist and amphibolite layer. Quartz is elongate mineral crystallizes in hexagonal crystal system consisting silica tetrahedra. Quartz grains present in vein has grain size from fine to medium. Quartz grains in vein shows blocky texture in which grains are equidimensional and randomly oriented. Quartz grains in veins shows undulose extinction and first order grey colour. Veins are categories based on the growth of mineral in the vein i.e., Syntaxial, antitaxial and ataxial growth. In syntaxial growth mineral crystal from the wall to the centre of the vein (Figure 21). In Antiaxial veins, mineral crystallize from the centre to walls. In ataxial, repetitive fracturing and crystallisation take place. The quartz veins present in study area are syntaxial vein growing from wall to the centre depicted by the larger and blocky grains at the periphery and smaller at the centre part of the vein. Quartz grains in the rock shows sutured, serrated and sinusoidal boundaries. (Stipp et al 2002) has shown that sutured and serrated are evidences of recrystallization. Grain boundary migration refers to the development of new boundaries. In grain boundary migration the atoms in a grain with the higher strain energy migrate by diffusion and neighbouring grain with lower strain energy which is also called as bulging (Winter, Principles of Igneous and Metamorphic Petrology, 2013). Bulging is observed in some quartz grains. Quartz crystals in veins are showing fluid trail. fluid inclusion appears as a dusty swarms formed by the penetration of fluid along fractures during healing of quartz grains. Quartz veins contains inclusions of calcite. Sub grains boundaries are straight and some are curved. Sub grains are vertical to sub vertical in some grains they are horizontal. Quartz vein is fractured and filled with secondary mineral like biotite calcite hornblende and plagioclase. Some biotite present near vein shows light yellow color in ppl whereas surround biotite from layers shows a dark brown colouration. Psuedotachilite vein crosscuts the quartz veins. Colourless lath shaped crystals are seen on both borders of the veins calcite in veins showing high order colours with twinkling and 2set cleavage. Polymineralic veins consist of hornblende, biotite, quartz, plagioclase and diopside. plagioclase grains inside the quartz veins have not been altered. Plagioclase grains do not have well defined straight boundaries but their boundaries are serrated, sutured, and curved. Polymineralic veins and opaque mineral appearing black veins seen in the section.

Psuedotachilite veins

Psuedotachilite are dark, irregular dendritic vein containing deformed suspended grains in glass like matrix which appears dark in color in cross polar setting. There are many micro psuedotachilite veins found in the thin section with or without suspended grains which are aligned parallel to the layer or vertical. Psuedotachilite veins formed by localized rapid fragmentation and melting due to shear heating generally attributed to earthquake or shock energy in dry rocks (Sibson, 1975; Vernon, 2004). The name derived from the basaltic glass tachilite. (Winter, 2013). Psuedotaclite veins (Figure 21) crosscuts all the layers seen in the section.

Hornblende veins

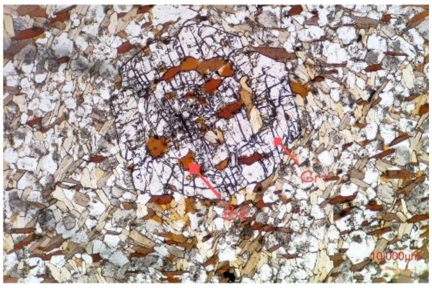
Green colored mineral with 2nd order interference color shows random orientation of grains. Enveloped by quartz veins on both sides (Figure 21). Grains in vein are radiating outwards from single point according to classification given by Vearncombe. Size variation is observed, larger grains are present mostly at central portion and smaller grains are present surrounding larger ones. These veins do not any alignment but crosscut by the psuedotachilite vein. Theses veins are composed of mineral hornblende.

Calcite veins

Calcites veins are found near quartz grain boundary's or present between quartz. Calcite crystal shows twinkling and high order interference color with 2set cleavage. Calcite mineral also seen surrounded by quartz grains.

Polymineralic veins

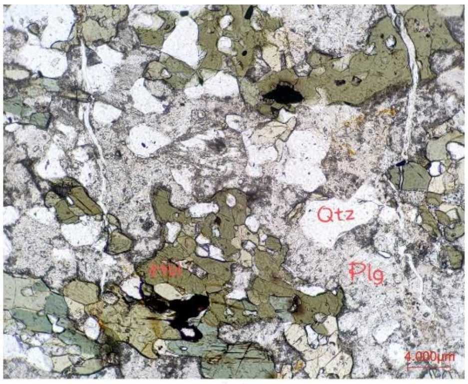
Polymineralic veins consist of biotite, hornblende, plagioclase, calcite, chlorite and diopside. Polymineralic veins are parallel to the quartz veins in the thin section. Minerals in these veins doesn't show any alignment or any deformation. Poly mineral vein is present with the quartz veins.



(a)

(b)

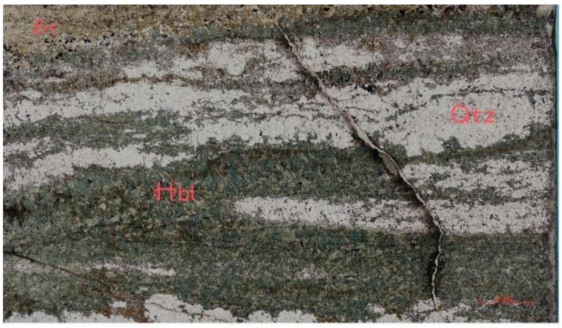
Figure 21 Thin section photograph showing synkinematic garnet forming around biotite.



(a)

(b)

Figure 22 Thin section photograph showing sausseritized plagioclase.



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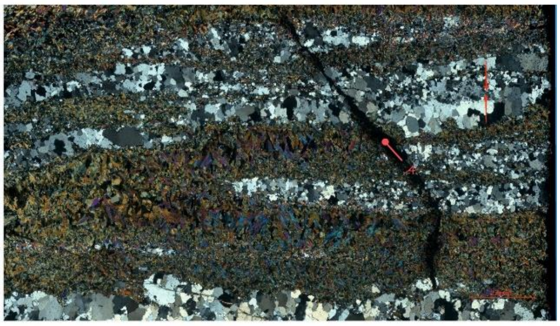
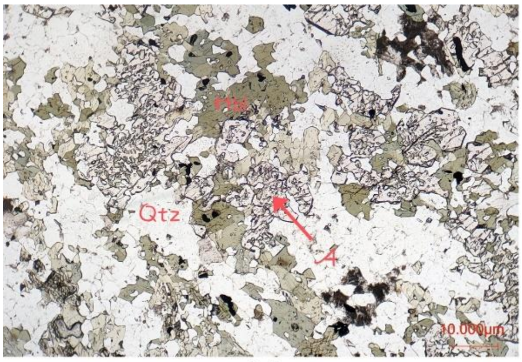


(b)

Figure 23 Thin section photograph showing syntaxial quartz vein (growth direction marked by red arrows). Point A is psuedotachilite vein.



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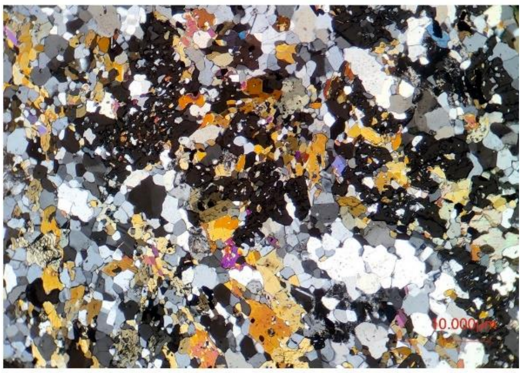
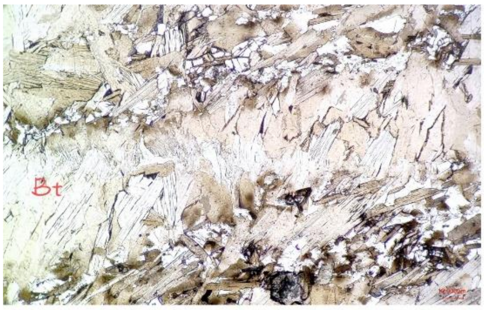


(b)

Figure 24 Skeletal garnets in hornblende layer



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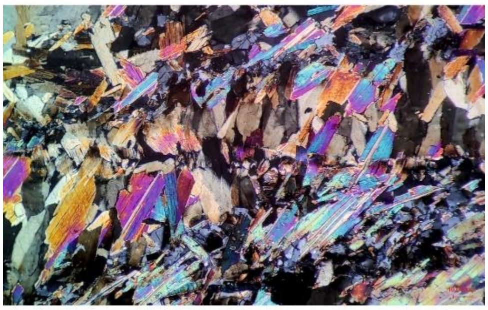

(b)

Figure 215 Kink band in biotite

EPMA

An electron probe micro-analyser, known as an electron microprobe or probe, is primarily utilized for the non-destructive chemical analysis of minute solid samples. Compared to a scanning electron microscope (SEM), it offers the additional capability of chemical analysis. EPMA's key advantage lies in its capacity to conduct precise and quantitative elemental analyses at extremely small "spot" sizes, often as small as 1-2 microns, mainly through wavelength-dispersive spectroscopy (WDS). This instrument's spatial resolution, coupled with its ability to produce detailed sample images, enables the examination of geological materials in their natural settings and the detection of complex chemical variations within individual phases, particularly glasses and minerals in geology. The electron optics in an SEM or EPMA allow for superior resolution imaging compared to visible-light optics, permitting the visualization of features that are imperceptible under a light microscope, facilitating the study of detailed microtextures or providing extensive context for individual spot analyses. EPMA analysis is most used method for geological sample analysis. EPMA analysis were carried out in IIT Bombay, India.

Based on the EPMA analysis data plots for garnet, biotite and plagioclase mineral was constructed. Most of the analyized minerals show very high Fe contents. Garnet mineral is rich in Fe content, based on the fluctuation in the Ca-Mg content which indicate Ca- mg exchange. As per plots and calculation the type of garnet found in the study area is almandine. Plagioclase in the section based on the EPMA calculation is Oligoclase. Based calculation Fe rich biotite seen in the rock.

Table 1 Electron probe micro analytic data and structural formulae for Garnet. Calculated on basis of 12 oxygen.

SiO2	37.57	37.5	37.52	37.44	37.46	37.53	37.73	37.39	37.57	37.39	37.67	37.79	37.83	37.68	37.49
TiO2	0	0.06	0.05	0.07	0.03	0.09	0.04	0.06	0.02	0.04	0.05	0	0.05	0	0
Al2O3	20.75	20.94	21.02	20.87	20.73	20.72	20.73	20.88	20.83	20.72	20.94	20.82	20.79	20.79	20.68
Cr2O3	0	0.05	0	0	0	0	0.05	0	0	0.01	0	0	0	0	0.04
FeO	32.75	32.81	32.83	32.74	32.65	32.2	33.19	32.81	33.07	32.69	33.18	33.8	33.92	34.58	34.07
MnO	4.37	4.42	4.15	4.12	3.75	3.76	3.75	3.46	3.12	2.95	2.79	2.69	2.23	1.66	1.85
MgO	1.27	1.3	1.25	1.29	1.38	1.25	1.33	1.42	1.43	1.42	1.5	1.52	1.61	1.65	1.59
CaO	4.41	4.43	4.59	4.63	4.86	5.25	4.66	5.02	5.26	5.42	5.01	4.78	5.12	5.07	4.9
Na2O	0	0.02	0.03	0.02	0.03	0.01	0.04	0.02	0	0	0	0.02	0.01	0	0
K2O	0.01	0.03	0.03	0	0	0.01	0	0	0	0	0	0	0.02	0	0.02
BaO	0	0	0	0	0	0	0	0.04	0.06	0	0.02	0.01	0	0	0.05
Cl	0.01	0.01	0	0.02	0	0	0	0.03	0	0.01	0	0.02	0	0	0.03
P2O5	0	0	0	0	0	0	0	0.01	0.04	0	0	0	0.01	0.01	0
F	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	101.14	101.57	101.48	101.19	100.88	100.83	101.52	101.15	101.4	100.65	101.16	101.44	101.59	101.47	100.72
Si	3.01	3.00	3.00	3.00	3.01	3.01	3.01	3.00	3.00	3.01	3.01	3.02	3.01	3.01	3.01
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.96	1.97	1.98	1.97	1.96	1.96	1.95	1.97	1.96	1.96	1.97	1.96	1.95	1.96	1.96
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	2.20	2.19	2.20	2.20	2.19	2.16	2.22	2.20	2.21	2.20	2.22	2.26	2.26	2.31	2.29
Mn	0.30	0.30	0.28	0.28	0.26	0.26	0.25	0.23	0.21	0.20	0.19	0.18	0.15	0.11	0.13
Mg	0.15	0.15	0.15	0.15	0.17	0.15	0.16	0.17	0.17	0.17	0.18	0.18	0.19	0.20	0.19
Ca	0.38	0.38	0.39	0.40	0.42	0.45	0.40	0.43	0.45	0.47	0.43	0.41	0.44	0.43	0.42
X_{Fe}	0.73	0.72	0.73	0.73	0.72	0.72	0.73	0.72	0.73	0.72	0.74	0.75	0.74	0.76	0.76
X_{Mg}	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
X_{Ca}	0.13	0.13	0.13	0.13	0.14	0.15	0.13	0.14	0.15	0.15	0.14	0.14	0.14	0.14	0.14
X_{Mn}	0.10	0.10	0.09	0.09	0.08	0.08	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.04	0.04

Table 2 Electron probe micro analytic data and structural formulae for Biotite. Calculated on basis of 11 oxygen.

SiO2	36	36.48	36.22	36.19	33.09	36.37	36	35.59	35.9	35.69	35.12	35.99
TiO2	1.84	1.91	1.82	1.89	5.37	1.82	1.68	1.82	1.78	1.74	1.83	1.56
Al2O3	17.03	17.2	16.81	16.75	14.94	17.05	16.75	16.64	16.57	16.32	15.91	16.33
Cr2O3	0.06	0	0.04	0	0.04	0.1	0	0	0.07	0.08	0.04	0.06
FeO	21.77	21.68	21.56	21.43	20.5	21.53	21.19	21.68	21.74	21.65	21.64	21.59
MnO	0	0.04	0	0.04	0.03	0	0.04	0.03	0.04	0	0.04	0.03
MgO	8.91	8.93	8.68	8.76	8.35	8.91	8.95	8.74	8.72	9.04	8.54	9.31
CaO	0.03	0	0.07	0	3.99	0	0.03	0	0.13	1.13	0.71	0.31
Na2O	0.26	0.26	0.25	0.25	0.14	0.21	0.35	0.24	0.52	0.67	1.94	0.43
K2O	8.76	8.9	9.03	9.08	5.55	8.81	8.81	9.01	7.78	4.89	4.73	7.17
BaO	0.13	0.17	0.16	0.16	0.07	0.12	0.2	0.16	0.06	0.01	0.03	0.12
Cl	0	0	0.02	0.01	0.04	0.01	0.02	0.04	0.03	0.06	0.34	0.06
P2O5	0.02	0.03	0	0	0	0.02	0	0	0	0	0.02	0.01
F	0	0	0	0	0.01	0	0	0	0	0	0	0
Total	94.82	95.61	94.67	94.55	92.13	94.95	94.02	93.94	93.34	91.28	90.92	92.97
Si	2.78	2.79	2.80	2.80	2.63	2.80	2.80	2.78	2.81	2.81	2.80	2.81
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.55	1.55	1.53	1.53	1.40	1.55	1.54	1.53	1.53	1.52	1.50	1.51
Cr	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Fe	1.41	1.39	1.40	1.39	1.36	1.39	1.38	1.42	1.42	1.43	1.45	1.41
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.03	1.02	1.00	1.01	0.99	1.02	1.04	1.02	1.02	1.06	1.02	1.08
Ca	0.00	0.00	0.01	0.00	0.34	0.00	0.00	0.00	0.01	0.10	0.06	0.03
Na	0.04	0.04	0.04	0.04	0.02	0.03	0.05	0.04	0.08	0.10	0.30	0.07
K	0.86	0.87	0.89	0.90	0.56	0.86	0.87	0.90	0.78	0.49	0.48	0.72
Ba	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.01
X_{Fe}	0.58	0.58	0.58	0.58	0.58	0.58	0.57	0.58	0.58	0.57	0.59	0.57
X_{Mg}	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.42	0.42	0.43	0.41	0.43

Table 3 Electron probe micro analytic data and structural formulae for Plagioclase. Calculated on basis of 8 oxygen.

SiO2	62.89	63.79	64.12	63.3	63.63
TiO2	0	0.01	0	0.02	0
Al2O3	22.69	23.18	23.18	23.83	23.46
Cr2O3	0	0	0.01	0.05	0
FeO	0.26	0.36	0.24	0.24	0.25
MnO	0	0.01	0	0.03	0
MgO	0	0.01	0	0	0
CaO	3.97	4.39	4.33	5.17	4.66
Na2O	9.59	9.77	9.86	9.35	9.69
K2O	0.07	0.06	0.06	0.06	0.05
BaO	0.01	0	0.01	0	0.03
Cl	0	0	0.01	0	0
P2O5	0	0	0.02	0	0
F	0	0.01	0	0	0
Total	99.47	101.58	101.84	102.05	101.77
Si	2.80	2.79	2.79	2.76	2.78
Ti	0.00	0.00	0.00	0.00	0.00
Al	1.19	1.19	1.19	1.22	1.21
Cr	0.00	0.00	0.00	0.00	0.00
Fe	0.01	0.01	0.01	0.01	0.01
Mn	0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.00	0.00	0.00	0.00
Ca	0.19	0.21	0.20	0.24	0.22
Na	0.83	0.83	0.83	0.79	0.82
X_{ca}	0.19	0.21	0.20	0.24	0.22
X_{Na}	0.83	0.83	0.83	0.79	0.82

Table 4 Electron probe micro analytic data and structural formulae for Hornblende. Calculated on basis of 23 oxygen.

SiO2	39.93	41.9	40.58	41.28	42.93	40.23	52.94	53.41	41.7	52.83
TiO2	0.38	0.3	0.46	0.32	0.32	0.3	0	0	0.31	0.02
Al2O3	15.6	16.6	16.62	16.08	14.16	15.56	0.43	0.38	15.98	0.9
Cr2O3	0.17	0.03	0	0.02	0	0.02	0	0.01	0.02	0
FeO	21.42	21.21	21.21	21.34	21.96	20.98	30.41	31.18	21.11	30.71
MnO	0.27	0.33	0.31	0.31	0.36	0.32	0.92	0.91	0.33	0.85
MgO	5.07	5.31	5.03	5.17	6.29	4.89	12.24	12.29	5.35	11.93
CaO	10.79	10.46	10.84	10.6	9.67	10.48	0.45	0.41	10.47	0.78
Na2O	1.75	1.69	1.76	1.74	1.36	1.46	0.07	0.05	1.6	0.1
K2O	0.47	0.42	0.51	0.38	0.37	0.43	0.02	0.01	0.36	0.04
BaO	0	0	0	0	0	0	0.04	0	0.03	0
Cl	0	0	0.01	0	0	0.02	0	0.01	0	0
P2O5	0.02	0	0.02	0	0.03	0	0	0.01	0	0
F	0	0	0	0	0	0	0	0	0	0
Total	95.87	98.27	97.34	97.26	97.44	94.68	97.54	98.66	97.27	98.17
Si	6.23	6.31	6.20	6.30	6.52	6.32	8.03	8.02	6.35	7.97
Ti	0.04	0.03	0.05	0.04	0.04	0.04	0.00	0.00	0.04	0.00
Al	2.87	2.95	3.00	2.90	2.54	2.88	0.08	0.07	2.87	0.16
Cr	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	2.79	2.67	2.71	2.73	2.79	2.76	3.86	3.92	2.69	3.88
Mn	0.04	0.04	0.04	0.04	0.05	0.04	0.12	0.12	0.04	0.11
Mg	1.18	1.19	1.15	1.18	1.42	1.14	2.77	2.75	1.21	2.68
Ca	1.80	1.69	1.78	1.73	1.57	1.76	0.07	0.07	1.71	0.13
Na	0.53	0.49	0.52	0.52	0.40	0.44	0.02	0.01	0.47	0.03
K	0.09	0.08	0.10	0.07	0.07	0.09	0.00	0.00	0.07	0.01
X_{Fe}	0.55	0.52	0.54	0.53	0.53	0.54	0.57	0.58	0.53	0.58
X_{Mg}	0.23	0.23	0.23	0.23	0.27	0.22	0.41	0.41	0.24	0.40
X_{Al}	0.22	0.25	0.24	0.24	0.20	0.23	0.02	0.01	0.24	0.02

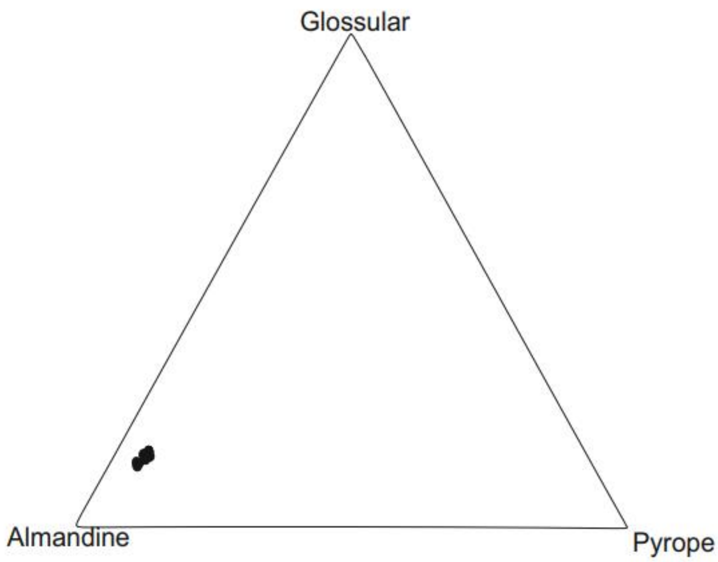

Figure 26 Ternary plot for garnet mineral based on the EPMA calculation.

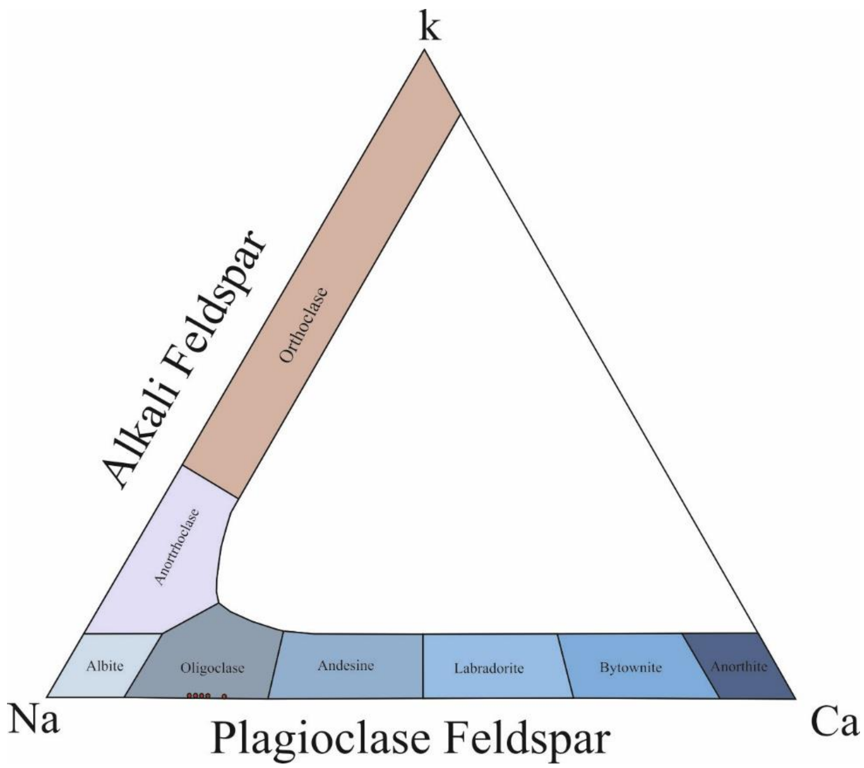

Figure 27 Ternary plot for plagioclase feldspar based on the EPMA calculation

Chapter 5

Geothermobarometry

5.1 Geothermobarometry

Geothermobarometry define as estimation of pressure and temperature condition under which the rock and mineral must have formed. Geobarometry focus on estimation of pressure and geothermometry focuses on the calculating peak temperature condition. Most commonly used geothermometer is garnet-biotite where Fe-Mg exchange takes place and these minerals are found in almost most of the medium grade metamorphic rocks. Exchange reaction can be written as

$$Mg_3Al_2Si_3O_{12} + KFe_3AlSi_3O_{10}(OH)_2 = Fe_3Al_2Si_3O_{12} + KMg_3AlSi_3O_{10}(OH)_2$$

The garnet biotite Fe-Mg exchange reaction based on the thermometric formulation were used to calculate temperatures. (Bhattacharya etal.,1992a,b, Ferry and Spear,1978, Holdway 2000, Kaneko and Miyano 2004, Kaneko, Miyano 2004a, Kleemann and Reinhardt 1994, Spear 1993, Ferry & Spear, 1978) thermometers used for calculation of temperature and (Wu, C.M., Zhang, J. and Ren, L.D. (2004)) was used for calculation of pressure using PTQuick software and the graph was generated.

Considering all the temperature calculated using garnet-biotite with different thermometer, temperature values estimated based on the Fe-Mg exchange of garnet-biotite highest temperature was recorded using Kaneko and Miyano 2004 which ranges between 541°C - 563°C.

Table 5 Table showing values of pressure and temperature after geotheremobarometry analysis.

	MINERAL-Assemblage					
Temperature in °C	Minerals/P,kbar	2	10	Thermometer		
	GrtBt	513	537	Kleemann and Reinhardt 1994		KR94
	GrtBt	526	549	Holdway 2000		H00
	GrtBt	428	454	Spear 1993		S93
	GrtBt	504	509	Bhattacharya etal.,1992a		BMMSR92a
	GrtBt	494	500	Bhattacharya etal.,1992b		BMMSR92b
	GrtBt	541	563	Kaneko and Miyano 2004		KM04
	GrtBt	521	542	Kaneko and Miyano 2004a		KM04a
	GrtBt	428	454	Ferry & Spear, 1978		FS78
	Geobarometer					
Pressure in Kbar (Wu, C.M., Zhang, J. and Ren, L.D. (2004)a,b	Minerals/T,°C	400	450	500	550	600
	GrtBtPl(Qtz)	7	8	8	8	9
	GrtBtPl(Qtz)	7	8	8	9	10

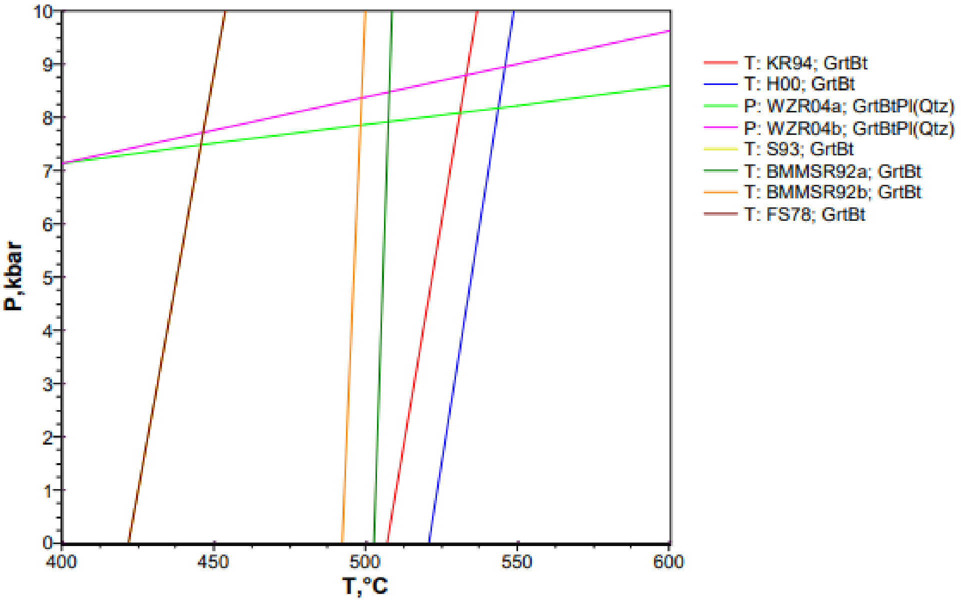

Figure 28 Pressure v/s temperature plot based on the EPMA data calculation using PTQuick Software

Chapter 6

Discussion and Conclusion

6.1 Discussion

The rock mostly observed in the study area is quartz biotite schist with or without garnets. In the field different macro structure like pinch and swell, folding, crenulations and en echelon was observed. The collected structure data was plotted using georient software for a better perspective and understand of the field relation. There are four steeply dipping foliation seen in the area. Steeply dipping N-S foliation was observed trend varying from N360°-N20° and dip amount was 60°-70 due east. Foliation is recorded in the northern part of the study area. Quartz veins present in the area were parallel to sub parallel to the penetrative foliation. Steeply dipping E-W foliation having trends between N90°-N120° with a varying deep amount towards north. Steeply dipping N130° foliation was the most dominant foliation observed in many outcrops. Most of the quartz veins in the study area show pinch and swell structure in this trend. Most of the veins lie parallel to sub parallel to this foliation and were steeply dipping or vertical. Steeply dipping N130° foliation was intrafolial to Steeply dipping N65° foliation based on this conclusion was derived that N65° foliation was younger then the N130° foliation.

The detailed petrographic studies of microstructure in biotite schist and quartz vein present in the biotite schist exposed Sawantwadi Sindhudurg district of southern Maharashtra. The most abundant minerals in the rock are Biotite, Hornblende, Quartz and Garnet. The biotite schist is composed of biotite + quartz ± Garnet ± plagioclase (sausseritized). The biotite schist is composed of biotite + quartz ± Garnet ± plagioclase(sausseritized) ± chlorite ± calcite and amphibolite composed of hornblende + diopside ± garnet + plagioclase(sausseritized) + scapolite ± calcite + iron oxide. Biotite is a dominant mineral that defines the tectonic fabric in biotite schist. The rock is layered Kink bands in biotite is seen in thin section (Figure 23). Kinking forms when slip on a single plane is inadequate to maintain homogeneous deformation. The biotite grain seen sharply bends and deformation localized into kink bands which enables shortening of the grain to continue. Kink band define as the part that undergoes rotation with respect to unkinked part of the grain. Quartz grain in the matrix shows undulose extinction. Undulose extinction form as a result of dislocation which forms and migrate so the portion of crystal lattice. This migration and reorientation crystal as the polarising position of the mineral depend upon the crystallographic orientation. Dislocations enhances the mineral capacity to accommodate stress (Winter, 2013). Quartz grains in the rock shows sutured, serrated, sinusoidal and straight boundaries. (Stipp et al 2002) has shown that sutured and serrated are evidences of recrystallization. Grain boundary migration refers to the development of new boundaries. In grain boundary migration the atoms in a grain with the higher strain energy migrate by diffusion and neighbouring grain with lower strain energy which is also known as bulging as per the description of the process provided by the (Winter, 2013). Bulging can be seen in the thin section. Garnet porphyroblasts are very common in the area. Porphyroblasts are most useful for determining deformation history and are more resistant to deformation. Porphyroblasts can be used as shear sense indicator. Garnets of various sizes are observed. Garnets present in the biotite layer shows idioblastic- subidioblastic texture i.e., euhedral with well define grain boundaries contains very few inclusions of quartz, plagioclase and biotite. Growth of garnet mineral can be further divided into different types on the basis of timing of growth during a deformation event i.e., pre-kinematic, syn-kinematic, inter-kinematic and post-kinematics (Winter, 2013). Garnets in biotite schist are syn-kinematic (Figure 22). Garnet with and without inclusions are present in thin section. Biotite grains present with the chlorite mineral grain layer shows different alignment the interkinetic chlorite mineral grains where chlorite grain boundaries are serrated and sinusoidal. Reduction in chlorite grain size and number of chlorite grains are observed towards biotite garnet rich layer. Plagioclase grains are showing alteration which is known as sausseritized.

Amphibolite schist are present which is composed of hornblende + diopside ± garnet + plagioclase(sausseritized) + scapolite ± calcite + iron oxide. Garnet grains are highly fractured and which contains inclusion of other minerals like quartz, plagioclase, hornblende and diopside. Amphibolite layer contains skeletal garnets which formed due to limited of mobility of ions. At greenschist and lower amphibolite facies condition, aluminium ions being less mobile than the other ions unless the pH is extremely low or high or if salinity is extremely high. Skeletal garnets (Figure 22) form in the Al poor domains. Hornblende shows decussate texture. Garnets in the biotite are idioblastic not fractured and hornblende rich layer have highly fractured garnet showing skeletal garnet.

Quartz veins precipitated in the fracture or cavities formed in the biotite schist. Grains blocky texture in which grains are equidimensional and randomly oriented. Quartz grains in veins shows undulose extinction and first order grey colour. The quartz crystal does show undulose extinction, most of the quartz grain shows serrated and straight boundaries except few, this shows that quartz vein must have been emplaced and experienced stress condition present during time of its formation. fluid trails appearing as dusty swamp seen in the grains of quartz. Previous works mention presence of the chessboard patten in the quartz which is a high temperature microstructure is not seen in this particular section. There is calcite present in thin section but cannot be observed in the field as calcite is an easily eroded there is a possibility of calcite veins being eroded. The quartz veins present in study area are syntaxial vein growing from wall to the centre depicted by the larger and blocky grains at the periphery and smaller at the centre part of the vein. Quartz veins contains inclusions of calcite. Sub grains boundaries are straight and some are curved. Quartz vein is fractured and filled with secondary mineral like biotite calcite hornblende and plagioclase. Polymineralic veins consist of hornblende, biotite, quartz, plagioclase and diopside. Plagioclase grains inside the quartz veins have not been altered. Polymineralic veins and opaque mineral appearing black veins seen in the section.

Psuedotachilite are dark, irregular dendritic vein containing deformed suspended grains in glass like matrix which appears dark in color in cross polar setting. There are many micro psuedotachilite veins (Figure 21) found in the thin section with or without suspended grains which are aligned parallel to the layer or vertical. Psuedotachilite veins formed by localized rapid fragmentation and melting due to shear heating generally attributed to earthquake or shock energy in dry rocks (Sibson, 1975; Vernon, 2004). Psuedotaclite veins crosscuts all the layers seen in the section. Hornblende veins consist of grains shows radiating outwards from single point. Veins do not any alignment but crosscut by the psuedotachilite vein which is an indicator that psuedotachilite veins are the last on to form. Polymineralic veins consist of biotite, hornblende, plagioclase, calcite, chlorite and diopside. Polymineralic veins are parallel to the quartz veins in the thin section. Minerals in these veins doesn’t show any alignment or any deformation. Poly mineral vein is present with the quartz veins.

EPMA analysis of the thin section was conducted. Based on the analysis geothermobarometry temperature and pressure was calculated. Rock has experienced temperature between 428°C-563°C and pressure of about 7-10 kbar.

6.2 Conclusion

The study area located in the Sawantwadi, Sindhudurg District of Southern Maharashtra region which contains metapelites and amphibolite greenschist facies series rock undergone series of deformation event contains quartz vein emplacements formed due to metamorphic process. Quartz vein present in study area shows different structure like crenulation, pinch and swell structures and folds. Based on the structure seen in the study area four generation of quartz vein emplacement was derived. First emplacement after the formation N-S foliation which are crenulated in E-W and pinch and swell structure in N-S. Second emplacement indicated by fold in vein whose axial plane is E-W along which are seen near sheath folds in NC 57. Third emplacement marked by formation pinch and swell structure in the quartz vein along N130°. Last fourth emplacement Seen in Sutarwadi where quartz veins are parallel to subparallel to the foliation. Quartz grains in the veins shows undulose extinction with serrated and few straight boundaries. Size of garnet crystal varies as it increases near to the veins and decreases as move away from vein. As per the results obtained after geothermobarometry analysis rock has experienced temperature and pressure between ~428°C- 563°C and ~7-10 kbar.

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