



Contrasting mineralogy and strain partitioning across N-S oriented Sitampundi - Kanjamalai Shear in Sitampundi Anorthosite Layered Complex

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Abstract: Sitampundi Anorthosite Layered Complex (SALC) is a complexly folded and metamorphosed terrain that shows different metamorphic grade separated by a regional linear divide. In the north-eastern part of the complex, the anorthosites contain green-colored clinozoisites that are strikingly absent in the western part of the limb. Based on the presence of the clinozoisites, the entire SALC can be divided into two zones. The Sitampundi-Kanjamalai shear zone (SKSZ) separates mega crystals of clinozoite bearing anorthosites from clinozoisite free anorthosites. To add furthermore, strain analysis of different samples of anorthosite on either side of the zones was conducted by employing Flinn method. In general, anorthosites fall into the flattening field. The clinozoisite free anorthosites are more flattening and clinozoisite bearing anorthosites exhibit a slight difference in their strain ratio, i.e., it is comparatively less flattening. Geochemistry of clinozoisites was studied using EPMA & XRD methods. The percentage of oxides obtained from EPMA coincides with that of epidote. But, XRD confirms the mineral to be clinozoisite indicating the transition phase of epidote to clinozoisite. Zoning has had occurred in clinozoisites with aluminium oxide rich core and FeO rich rim. This could be related to a retrogression corresponding to a shearing event.

Keywords: Sitampundi Anorthosite Layered Complex (SALC), Sitampundi - Kanjamalai Shear, Strain analysis, Clinozoisites, Zoning, Thirumanimuthar river.

1. Introduction

Sittampundi anorthosite is metamorphosed and with linear arrangement of bands of feldspars and amphiboles giving a gneissose structure hence known as Sittampundi Meta-Anorthosites Layered Complex (SMALC). The Sitampundi Anorthosite Layered Complex (SMALC) occurs in Tiruchengode taluk of Namakkal dt, Tamil Nadu. The study area falls within the Survey of India (SoI) Toposheets 58 I/3, I/4, E/15 and E/16 (Figure.1).

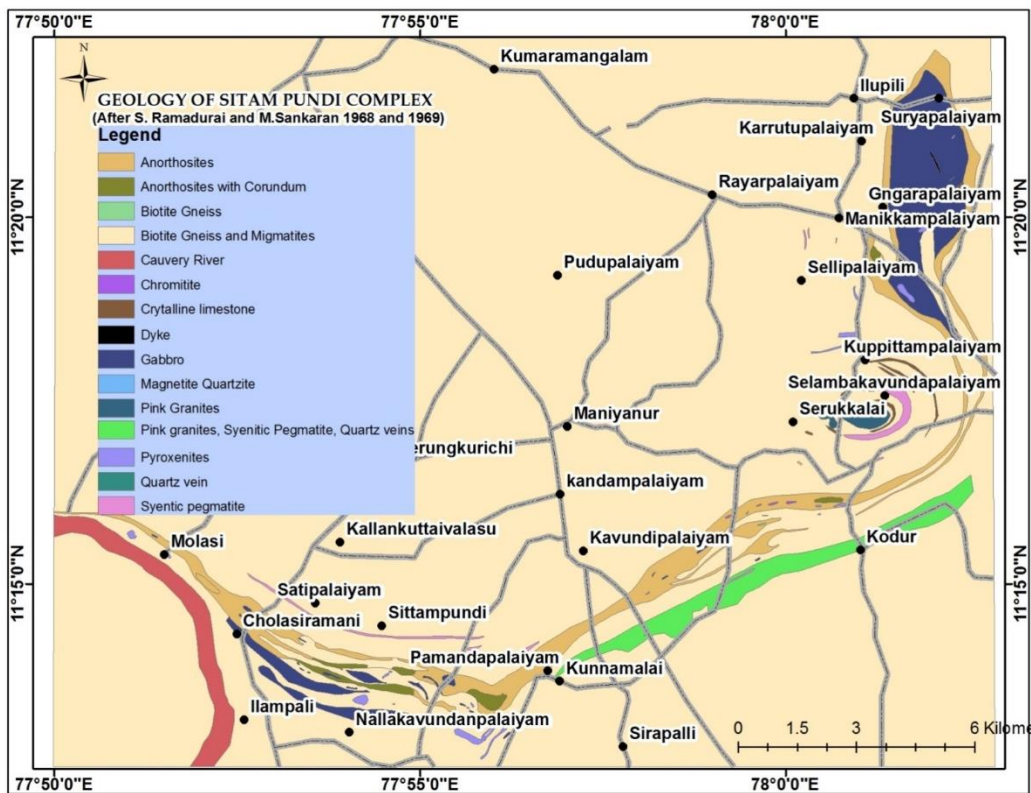


Figure 1. Petrological Map of SALC, (Modified after Subramaniyam, 1956)[1]

Nehru (1955) [2] has studied the Sitampundi complex and considered them as high-grade metamorphic assemblages whereas Subramanyam (1956) described them as layered igneous complex. [3] denoted them as metamorphic assemblages formed from marly and politic sediments. [4] has described the following igneous stratigraphy from the bottom upwards: gabbro with pyroxenite inclusions, chromite-layered hornblende anorthosite and clinzoisite-anorthosite and stratigraphy is only well preserved in the north-east of the area. The complex has been folded into an isoclinal antiform with the result that the stratigraphy is duplicated in two-fold limbs which are locally separated by gneiss and refolded.

This second phase of open folding has given rise to the present form of the complex as a major interference pattern. Linear mineral fabrics largely formed in association with the first deformation. The complex is a tectonic remnant of a layered igneous body that has been recrystallized and deformed. [5] described the hornblende in the meta-anorthositic rocks, which are pyroxene-free, is meta-morphic in crystallization from the texture and the hornblende composition and uncertain about its derivation from metamorphism of pyroxene, olivine and plagioclase is uncertain. [6,7] have indicated geochronological data of the layered complexes points to emplacement at c. 2.9 Ga. A suite of felsic magmas now represented by enderbite and charnockite (felsic orthogneiss) subsequently intruded the members of the

Sitampundi layered complex. The entire assemblage of mafic, ultramafic and felsic rocks underwent deformation accompanied by high-grade metamorphism at ca. 2.450-2.45 Ga and by amphibolite facies metamorphism during ca. 0.72-0.50Ga [6,7]. The high-grade metamorphism followed by retrogression but the intensity of retrogression uniform is the question of debate. The present study started with field observation of green color Epidote - Clinzoisite mineral and absence of corundum in the eastern limb.

Geological setting

Sitampundi complex form a arcuate layered metamorphic complex along the southern part of Northern part of Southern Granulite Terrain (SGT) within Namakkal block (Behara et al., 2019 and reference therein). Observations are indicative of a collisional environment in which the Salem Namakkal Subterrane was accreted in the mid-Archaean. SGT preserves the lithology and crustal history for nearly 2.5 Ga [9]. South of the Salem-Attur shear zone (SASZ) to Palghat Cauvery shear zone (PCSZ) is referred to as Salem-Namakkal Subterrane. The metamorphosed rocks consists of gabbro, pyroxenite, amphibolite and anorthosite interlayered with chromitite, with the original stratigraphy overprinted by high-grade metamorphic assemblages. The entire sequence is preserved as remnant tectonic lenses in a linear arcuate belt within hornblende-biotite granodiorite and tonalite gneisses in the southern granulite terrain (SGT). The area has been subjected to ultra-high temperature (UHT) metamorphism (peak conditions ~ 20 kbar and 1020°C during the end of the Proterozoic [10].

The emplacement of Sitampundi layered complex protolith were between 2.9 and 2.54 Ga [6] and protoliths of the enclosing felsic gneisses intruded at ~ 2.51 Ga [12], and these rocks underwent polyphase deformation with granulite to upper amphibolite facies of metamorphism that affected the rocks of the layered magmatic complexes and the enclosing felsic orthogneisses between 2.48 and 2.45 Ga [11,7,12,8]. After the termination of the early Paleoproterozoic tectonothermal activities, sediments deposition took place on the granulite basement during $\sim 1.0-0.80$ Ga [9] then felsic to mafic to alkaline magmas intruded at $\sim 0.8\text{Ga}$, and followed by deformation. Finally upper amphibolite facies metamorphism occurred in the span of $\sim 0.65-0.50$ Ga [9]. Intrusions of sankagiri granite and granitic pegmatite in the span of 0.56-0.45 Ga mark the last major event in the NGT [13].

Structure

Sitampundi complex has witnessed polyphase deformation and has undergone last phase of major upper amphibolite metamorphism contemporaneous to the Sankagiri Granite emplacement associated shearing. The present state of the Complex is considered to be due to two major deformation episodes. Of which, the first gave rise to an Isoclinal Antiform with the fold axis plunging in the north-east direction. Second deformation has resulted in the now present curved structure of the complex. It is an open fold, plunging towards the south [4]. The thickness of the layering is not uniform, the western limb is less complex or not clear due to intense cultivation whereas the eastern one is highly folded like a loop. The presence of

clinozoisite could be attributed to the difference in intensity of folding [14]. But the presence of the clinozoisite large crystals is absent on the western side of the Thirumanimutharu river across N-S oriented Sitampundi-Kanjamalai shear. According to Subramaniam (1956) [1], epidote was also formed during the two periods of Archean metamorphism indicating that there might have existed two hydrothermally active regions. But this hydrothermal activity must require a shear plane which could be the north-south orienting Sitampundi-Kanjamalai Shear zone. The mylonites are exposed in narrow bands prominently close to Unjanai and near Morepalayam [15]. This shear zone exhibits σ , δ and φ type porphyroclasts are present where the σ and δ clasts are indicating dextral shear. The shear zone is swerving after Morepalayam and terminates against Moyar Bhavani Salem -Attur Shear Zone. But the Southern termination against Sitampundi layer complex is unclear. The Eastern side of Sitampundi Layered complex might have under-went the recrystallization corresponding to the shearing episode brought in by emplacement of Sankagiri Granites.

Strain Analysis of Anorthosites in SALC

Introduction

Flinn (1962) introduced the concept of deformation path in structural geology. Elliott (1972) and Ramberg (1975) discussed the mathematical formulation of this concept. Strain analysis is one of the important techniques of structural geology that measures and gives a quantitative relation to the degree of deformation in rocks. There are several methods, like Flinn method, Fry method, vorticity, R_{xz}/β methods for determining the strain pattern. Here, Flinn method has been used for analyzing the strain pattern in anorthosites.

Flinn method was adopted for the strain analysis of anorthosites in Sitampundi Anorthosite Layered Complex (SALC). L & T thin sections were prepared from three oriented anorthosite samples collected along SALC (figure - 2). Microphotographs of the thin sections were taken using the microscope.

Table 1. Spatial & structural data of samples

Sample No.	Latitude	Longitude	Strike	Dip	Dip Direction	Place
1	11.33011	78.02211	N4°	70°	SE	Kengarapalayam
2	11.22717	77.91936	N110°	76°	NE	Near Anamaarkoil
3	11.230549	77.940507	N59°	85°	SW	Four Road Junction

Flinn Method

This is one of the common methods for analyzing the strain pattern. This method requires both data from L-sections as well as T-sections. The software 'ImageJ' was used to measure the aspect ratio of the feldspar grains, by measuring the elliptical shape of deformed feldspar grains that must originally have been circular, it is possible to make a quantitative analysis of the strain pattern in deformed rocks by multiple measurements of the grains under

the prepared thin sections. The L-section data provide X/Z values (ratio of large axis to the small axis) and T-section data provide Y/Z values. From these values, X/Y values are determined and the flinn diagram is plotted with Y/Z values in the X-axis & X/Y values in the Y-axis. The resulting plot indicates that the anorthosites fall into the flattening field (figure - 3). The clinozoisite free anorthosites are more flattening and clinozoisite bearing anorthosites exhibit a slight difference in their strain ratio, i.e., it is comparatively less flattening.

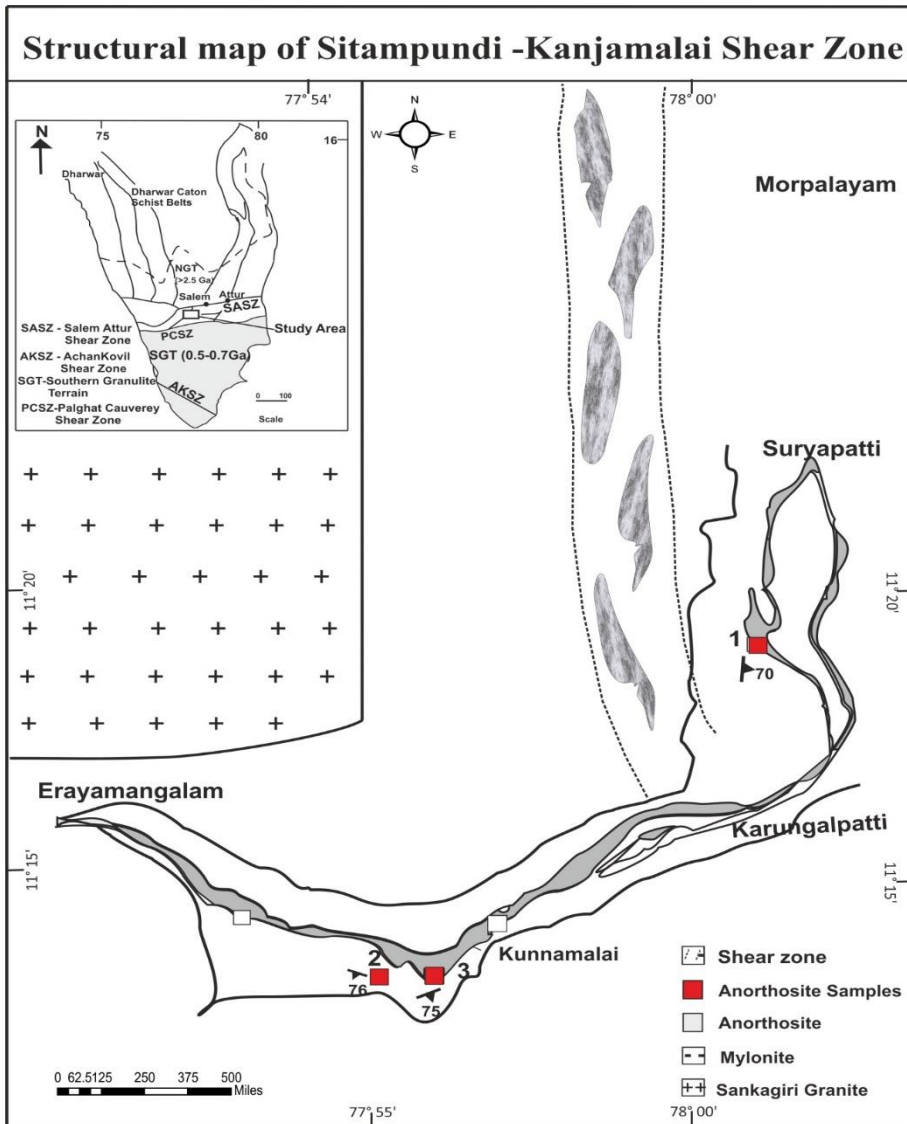


Figure 2. Structural Map of Sitampundi Anorthosite Layered Complex (SALC)

Thus, the meta-anorthosites have undergone differential metamorphism across N-S oriented Kanjamalai-Sitampundi shear. Recrystallization of crystals has taken place in the eastern limb, forming clinozoisite crystals.

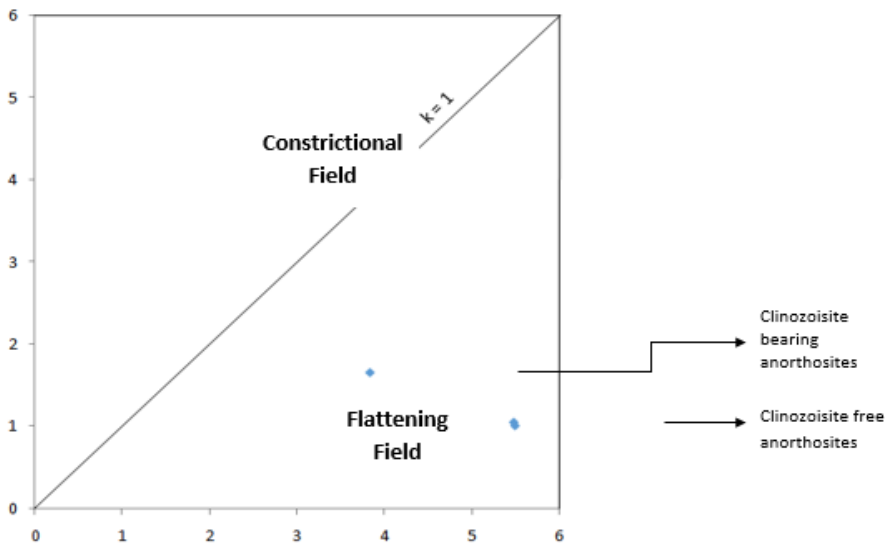


Figure 3. Flinn Plot (Y/Z vs X/Y) for feldspar grains from three thin sections (L & T sections) of Anorthosites

Petrography of - Clinzoisite bearing Anorthosite

In hand -specimen the mineral is pale pistachio green to yellow green occurs as disseminated grains with parallelism. Clinzoisite occurs in these rocks as oriented euhedral and subhedral crystals, displaying preferred orientation. The epidote-clinzoisite group of minerals in some of these rocks also displays a parallelism similar to the hornblendes (figure.4a). The mineral tends to replace anorthitic plagioclase and tend to develop crystal form. The clinzoisite in the anorthosites is generally show composition transition to epidote.



Figure - 4: a) Epidote-Clinzoisite bearing anorthosite near Kumaramalai, **b)** Residual hill of anorthosite,

A. EPMA

Samples of anorthosites containing epidotes were collected near Iluppili and they were used for Electron Probe Micro Analysis (EPMA)(Table-2). Firstly, thin sections of the samples were made in the laboratory at the Department of Earth Sciences, IIT-bombay. The samples were cut into small pieces and suitable pieces were selected for thin section preparation. They were finely polished using different meshes in decreasing order of mesh size up to 1 micron(μ). Then, the polished sample pieces were mounted over thin glasses which were polished in the similar way. The thin sections so made were sent for EPMA test to EPMA Lab at IIT-bombay.

Table 2. spatial data of clinozoisite bearing Anorthosite samples

Sample No.	Latitude	Longitude	Place
A1	11.33506	78.04011	Near Iluppili
A2	11.33506	78.04011	Near Iluppili

The results show that anorthite is dominating among other calcic-plagioclases namely andesine followed by labradorite. Sphene is found to be rich in Ti and Ca. Epidote is of our interest here. The range of Al_2O_3 percentage is 22.16 – 28.27 and the average percentage value of aluminium oxide is 24.86. The range of FeO percentage is 5.73 – 11.23 and the average percentage value of ferrous oxide is 8.38. The CaO percentage is between 23 and 24. A pattern could be noted from the Al_2O_3 and FeO values. As the value of aluminium oxide increases, FeO value decreases and vice versa. It could be interpreted that some replacement reactions between Al^{3+} and Fe^{2+} ions during deformation and hydrothermal activities had occurred.

Low diffusion rates chemical zoning is a common feature in minerals of the epidote group [19]. Growth zoning is common that is often modified by retrograde dissolution-precipitation [20] This is due to the changes in P-T conditions [19] and is strongly influenced by the miscibility gaps in the solid solution series and by the zoisite-clinozoisite phase transition [21]. From Back Scattered Electrons (BSE) images, zoning in epidotes could be identified. The core is rich in aluminium oxide whereas the rim is rich in FeO. Epidotes of Al-rich inner zone and Fe-rich outer margin may be related to an initial prograde metamorphism subsequently followed by a retrograde event (An Introduction to Rock-Forming Minerals Deer Howie Zussmann,1992) [22] It can be inferred that the metamorphism might have taken place initially at high temperatures with the emanating hydrothermal fluids followed by a rapid decrease in temperature that has resulted in retrograde metamorphism. The crystallization of aluminium rich zone indicates higher metamorphic temperatures (An Introduction To Rock-Forming Minerals Deer Howie Zussmann,1992) [22].

At the anorthite – epidote contact, the FeO content in epidote is high and it decreases away from the contact. In the case of aluminum oxide content, it is the exact vice versa of the above said condition. Some specks of epidote are found to occur within anorthite crystals and

few specks of anorthite are found to occur within epidote crystals. The results of the test are attached in the annexure.

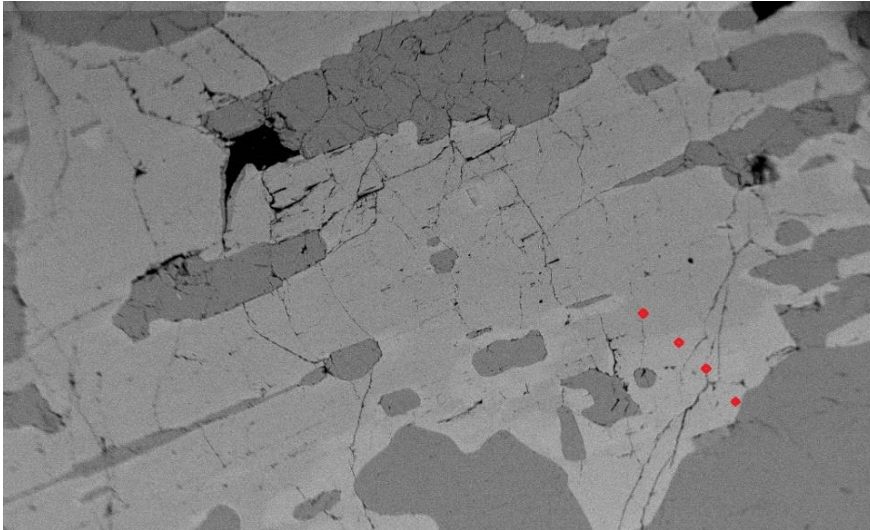


Figure 5. BSE image of anorthosite - clinzoisite thin section; Al content increases and Fe content decreases from point 1 to point 4.

B. XRD

The green-colored mineral crystals in the anorthosite were manually separated, grounded to powder in a mortar and then tested using XRD method.

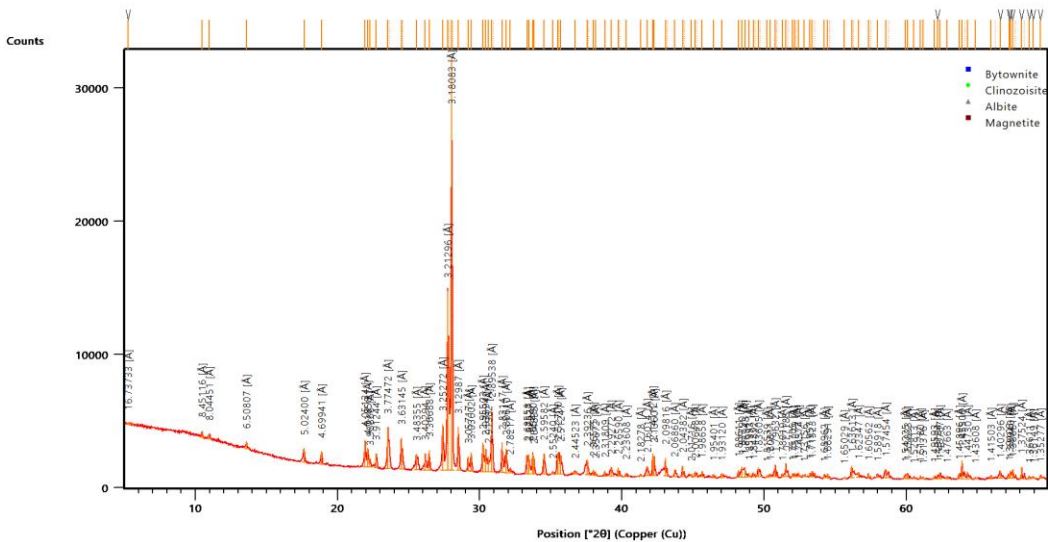


Figure 6. XRD graph for anorthosite sample: 2θ values, wavelengths of minerals and their corresponding counts

The test was done at the Department of Earth Sciences, IIT-bombay. From the test results, the mineral is identified as Clinzoisite.

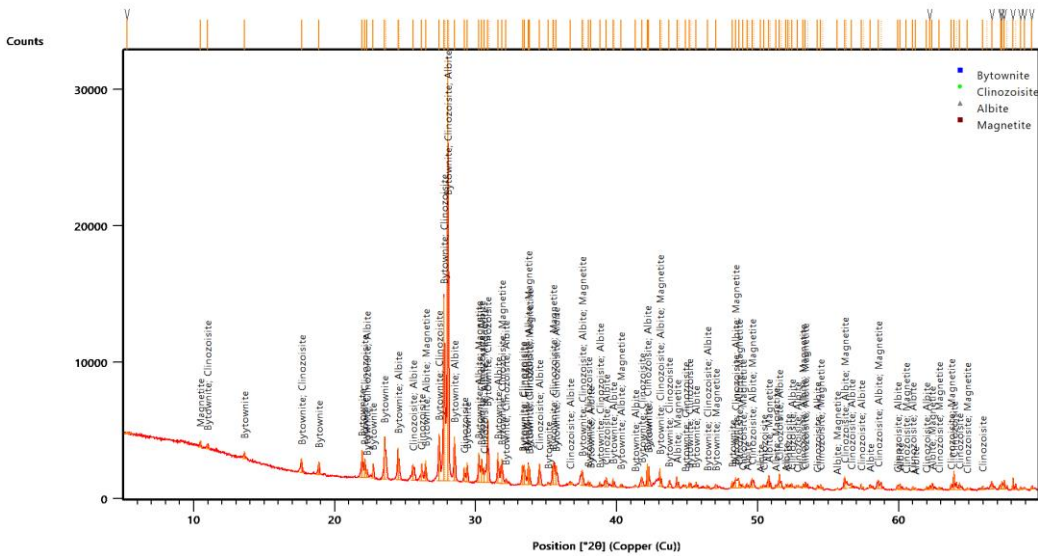


Figure 7. XRD graph for anorthosite sample: 2θ values, minerals and their corresponding counts

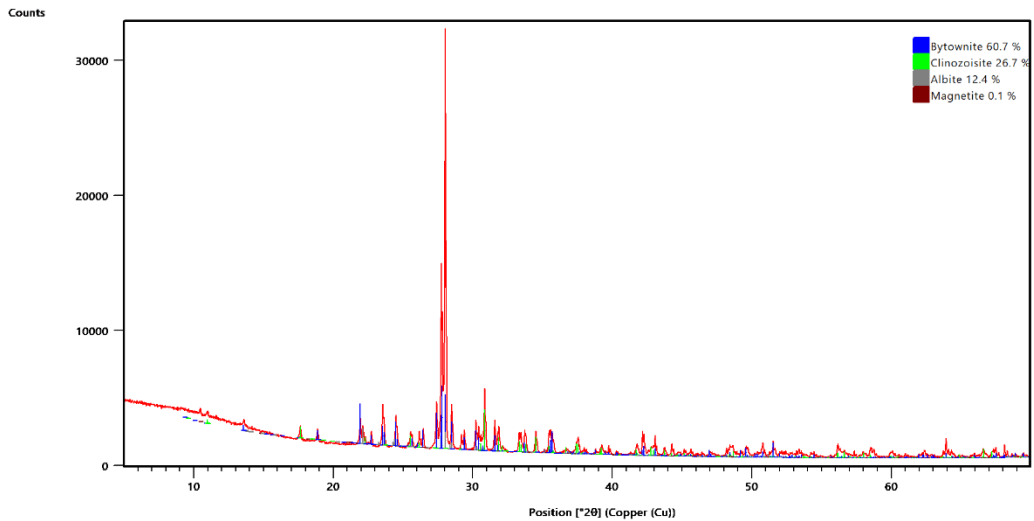


Figure 8. XRD graph for anorthosite sample: mineral counts in percentage

The XRD method of analysis indicates that the mineral is clinzoisite, whereas, EPMA indicates the presence of both epidote and clinzoisite based on their oxides' percentage which

denotes the zoisite-clinozoisite transition.

Corundum

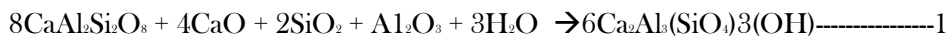
Corundum can form from magmatic crystallization or from High pressure (HP) / Ultra High Pressure (UHP) metamorphism or through anatexis [23]. Prismatic clinozoisite is present in the plagioclase-amphibole matrix and defines a crude banding, Individual grains of these minerals rarely show internal strain (undulose extinction). This feature suggests that the growth of amphibole and clinozoisite could be during deformation. Corundum occurs as individual crystals and never shares direct contact with amphibole but surrounded by corona of green spinel and plagioclase and sometimes contain inclusions of plagioclase [23]. The absence of corundum and spinel is striking and that the epidote-clinozoisite group of minerals in some of these rocks also displays a parallelism similar to the hornblendes, but the corundum crystals in them, insofar as noticeable, grow with their axes across the lineation.

Discussion

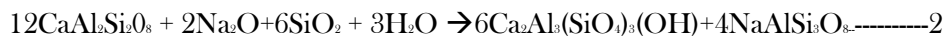
The anorthosites of the Sitampundi layered complex are extremely aluminous in bulk composition, contain corundum in varying proportions. The presence of corundum is confined to western part of Karungalpatti region and their absence in east signifies a change in environment. Thus, the entire layered complex can be divided into eastern and western complex with Sitampundi- Kanjamalai Shear Zone as its divider.

Corundum was presumably developed in the anorthosite of the SLC through vapour present incongruent melting of highly calcic plagioclase (An>95) during UHT metamorphism at temperature ≥1000°C and at 9 kbar (or higher pressure) along a geothermal gradient of ~33 °C/km [23]. A retrograde P-T path with an initial steeply decompressive segment that was succeeded by a weakly decompressive P-T path, presumably, partially replaced corundum + amphibole to form spinel + anorthite coronae in western part of the complex.

The rocks of the anorthosites of eastern side contain varying proportions of the epidote-clinozoisite group of minerals, and the following assemblages occur frequently: (1) anorthite, corundum, clinozoisite; (2) anorthite, clinozoisite, garnet (grossularitic); and (3) anorthite, clinozoisite, hornblende. While more mafic anorthite rocks are relatively free from this mineral, the felsic anorthosites carry a fair proportion [1].



Anorthite clinozoisite



Anorthite clinozoisite + albite



Anorthite clinozoisite + quartz + corundum

(After Turner (1948, p. 121-122) [24].

The equation 1 suggests the formation clinozoisite from anorthite requires silicification through fluids along with alumina and equation 2 exhibits the possibility of formation of clinozoisite directly from high silicic fluids rich in alkalis. Simple hydration of anorthite may produce clinozoisite and corundum but which is not possible as corundum generally believed to be formed by UHP metamorphism. Moreover they never had the direct contact with clinozoisite and hence it implies that the retrogression phase has produced clinozoisite from anorthite. The newer crystallization of clinozoisite could have modified and reduced the flattening of anorthite minerals.

If the fluid migration is considered to be the main agent in bringing the regrade recrystallization, then the pathways could be by the North-south oriented Sitampundi-Kanjamaalai Shear zone. The shear zone might have the divide for this layered complex having different mineral assemblages across. The newer recrystallization can be further confirmed by the portioning in strain determined by Flinn plot. Though both samples of anorthosites from either side of Sitampundi Layered complex falls in flattening field there is clear difference in the values i.e., the anorthosites with clinozoisite is less flattening then the anorthosite from western side.

Conclusion

This complex containing meta-anorthosites exhibits contrasting mineralogy on its either side. Corundum with spinel /sapphirine coronae in the central portion indicates UHP metamorphism. Clinozoisites, with zoning, embedded as crystals in anorthosites indicate metasomatic hydrothermal activities with a retrogressive character. Forceful intrusion of younger granite domes up the complex brought in considerable mineralogical changes, induced by mineralizers from the granite, with consequent formation of epidote-clinozoite minerals. The newer recrystallization in eastern limb where predominant clinozoite mineralization is prevalent had modified the strain pattern. The Sitampundi-Kanjamaalai Shear zone could be the principal causative parameter that brought in mineralogical and structural changes in the eastern and western part of Sitampundi Layered anorthosite complex.

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