CHAPTER 4. PETROGRAPHY

4.1 Introduction

The petrographic analyses revealed the textural characteristics and the mineralogy of the calc-silicates rocks under study. The results of the microscopic examination of 70 thin sections of the calc-silicate rock samples as well as the other associated rock types, viz. quartzites, metapelites and granites are discussed in the following pages.

In addition to the petrographic characterization of calc-silicate rocks, significant petrographic features and relevant mineral reactions as reflected from critical textures of the rock have been mentioned. It is pertinent to mention that the solid solution compositions of different phases as described in this chapter have been taken from mineral chemistry data (Chapter 5).Back Scattered Electron (BSE) images of major and important calc-silicate minerals and reaction textures have also been presented. Visually-estimated modal amounts of minerals within representative calc-silicate rocks are listed in Table 4.1.

Similarly, the process of development of new minerals within calc-silicate rocks in response to various metamorphic events associated with the phases of deformations (D_1 to D_3 and syn to post D_3 phase) has been presented in a Table 4.2 (modified after Mamtani et al., 2001) depicting time relationship between crystallisation and deformation.

4.2 Petrographic characteristics

4.2.1 Calc-silicate rocks

The calc-silicate rocks are characterized by the prominent hornfelsic/granofelsic texture which is defined by unoriented amphibole needles (Bhaskar Rao,1986),(Fig 4.1a). Apart from this, the porphyro-poikiloblastic texture and the granoblastic polygonal groundmass can be observed as the minor textures.

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* Parts of this chapter are based on our papers published:

(a) Akolkar G, Joshi A U, Limaye M A and Deota B S 2018 Implication of Godhra granite emplacement on calc-silicate rocks of Lunavada Region, NE Gujarat; J. Geosci. Res. **3** 147-152.

(b) Akolkar G and Limaye M A 2021 Mineral chemistry and reaction textures of calc-silicate rocks of the Lunavada region, SAMB, NE Gujarat; Journal Geological Society of India **96**,151-157. DOI:10.1007/s12594-021-1646-x

Groundmass is composed of quartz and microcline in some samples whereas in some samples it is made up of quartz, microcline and calcite.According to Winter (2010), granoblastic polygonal groundmass in which grain boundaries meet at the triple junction with an approximate 120º angle between them is the product of the grain boundary area reduction process occurring in structurally isotropic quartz grains.

These calc-silicate rocks possess a typical mineral assemblage as actinolite + diopside + quartz + titanite + calcite ± microcline ± biotite ± epidote ± plagioclase feldspar ± scapolite ± chlorite ± ankerite along with minor apatite, zircon and ilmenite. As these hornfelses are having a higher amount of Ca-silicate minerals like actinolite, diopside, titanite, epidote and scapolite, they are also termed as 'skarns'(Spry,1969). Few of these calc-silicates are biotite rich, few are epidote rich and few are scapolite bearing.

According to Mamtani et al.,(2001) the rocks present in and around Lunavada had undergone three phases of deformation, viz. D_1,D_2 and D_3 which led to M_1, M_2 and M_3 metamorphic events. According to him, the thermal event of Godhra granitic intrusion was experienced by the rocks of this region after regional metamorphism. This event was syn to post D_3. Due to this event, earlier features of regional metamorphism got obscured as the contact metamorphic textures appeared predominantly within these rocks. A vague occurrence of regional metamorphic features is noted in the form of occasional appearance of preferred orientation of actinolites as well as kinks present within biotites (Fig.4.1b and 4.1c) respectively.

Some important optical properties of minerals observed within these rocks and the probable reactions of their formations are as follows:

Actinolite

Actinolites present in these rock sections exhibit colourless to pale green pleochroism and moderate relief. Second to third-order interference colours as well as inclined extinction is observed. Different shapes are shown by these grains, i.e. acicular, bladed and sometimes fibrous. Due to their cleavage on (110), occasionally these actinolites assume the rhombic or pseudohexagonal shape and most of the times develop beads or strands-like appearance. Simple twinning is shown by few actinolite grains. Apart from unoriented as well as oriented actinolites, star-shaped actinolites can also be observed in rare cases (Fig.4.1d,4.2a). In that case, it appears like a flat rounded mass is present at the centre and needles are radiating in all directions from this mass. The average crystal length of actinolite needles ranges from 0.45 cm to 1.1 cm.

In calc-silicate rocks with oriented needles, actinolites and matrix of quartz are found to be segregated in such a way that alternate dark and light-coloured bands like pattern develops. Actinolite needles present within these calc-silicates are comparatively slender and most of them are devoid of any inclusion.

Poikiloblastic actinolites have also been observed which incorporate the inclusion trails of associated minerals like quartz and diopside grains which have a concordant relationship with groundmass fabric, i.e. $S_i = S_e$ (Fig.4.1e, 4.2b).Quartz inclusions show sharp extinction. According to (Ghosh, 1993 and Passchier and Trouw, 2005) sharp extinction of quartz inclusions within any mineral suggests post-tectonic development of that mineral porphyroblast.

Diopside

Subidioblastic diopside grains are distinguished by high positive relief, inclined extinction, weak pleochroism, high birefringence and two distinct sets of cleavages crossing almost at 90^{o} angles. In some sections, highly fractured diopside grains are also observed. Textural evidence of progressive metamorphism can be shown with the help of reaction texture viz. enclosed carbonate phase by Fe-rich diopside, i.e. salite (Ref. Chapter 5) in the matrix of quartz. Thus it can be stated that the salite is getting formed at the expense of the former.

Since the salite is Fe rich variety of diopside, the carbonate phase on account of which it is getting produced must be ankerite i.e Fe rich carbonate (Fig.4.1f).Thus the formation of salite can be given by the following reaction:

$$\text{Ankerite} + 2\,SiO_2 = \text{Salite} + 2CO_2$$

Actinolite porphyroblasts show numerous inclusions of salite. This texture suggests that the salite is breaking down to actinolite (Fig.4.1g, 4.2c) which is a retrograde reaction and is given as follows:

$$5\,\text{Salite} + H_2O + 3CO_2 = \text{Actinolite} + 3CaCO_3 + 2SiO_2$$

Quartz

Anhedral quartz grains can be seen with the modal amount varying from 8-40% and show low negative relief. It has been observed that the granoblastic polygonal texture shown by groundmass made up of quartz is common within the calc-silicates lying closer to granitic body while this feature is very poorly developed in the calc-silicates lying away from granite.

Titanite

Titanite possesses bold relief, high birefringence and weak pleochroism. Titanite grains within these calc-silicates are found to be closely associated with ilmenite in the matrix of quartz + calcite (Fig.4.1h). The probable reaction leading to their formation is:

$CaCO_3$ + SiO_2 + Ilmenite = Titanite + CO_2, which is a prograde reaction. Rarely, Wedge or spindle-shaped titanite is seen with good prismatic cleavages (Fig 4.2d).

Calcite

Anhedral calcite can be seen and is distinguished by good cleavages, low relief and extreme birefringence.

Microcline

Anhdral to subhedral microcline shows good cleavages. It is abundant (~12-15%) in most of the sections and exhibits its typical cross hatching pattern.

Biotite

Subhedral biotite grains are present which show pleochroism from colourless to brown. Moderate relief and perfect cleavages can also be seen. In some of the specimens of calc-silicate rocks, biotite laths can be observed to be nucleating along the margins of actinolites and are associated with microcline (Fig.4.1i,4.2e).

This indicates the following reaction,

3 Ca-amphibole + 5 K-feldspar + 6 CO_2 + 2 H_2O = 5 Biotite + 6 Calcite + 24 Quartz

Alteration of biotite to chlorite forms an interdigitation-like appearance. This alteration is on account of hydrothermal action (Parry and Downey, 1982).Similarly, numerous pleochroic haloes are present in biotites indicating the presence of radioactive minerals within them .

Epidote

Epidote grains are anhedral and have been observed as granular aggregates. They have high relief, weak pleochroism and parallel extinction. High-order interference colours are shown by them.

Epidotes present in these calc-silicates are frequently associated with actinolites (Fig. 4.1j,4.2f). The appearance of the epidote marks the threshold of the change from greenschist to epidote-amphibolite facies in regionally metamorphosed rocks (Deer et al.,1985). Epidote-actinolite association indicates the probable reaction of its formation as follows:

$$3\ \text{Chlorite} + 10CaCO_3 + 2SiO_2 = 2\ \text{Epidote} + 3\text{Actinolite} + 10CO_2 + 8H_2O$$

Thus the appearance of epidote within these rocks can be considered to be of the syn-D_2 phase of deformation which led to the $M_{2\text{-}1}$ metamorphic event.

Plagioclase feldspar

Fine to medium-sized tabular, subidioblastic grains of plagioclase shows their typical polysynthetic twinning. It makes only ≤ 1% of the mode.

Scapolite

Scapolite grains possess anhedral to subhedral shapes and are found to be forming columnar aggregates or granular clusters and exhibit moderate relief as well as prominent cleavages and are associated with calcite and microcline. Exceptionally, this scapolite is biaxial negative and exhibits third-order interference colours. Some of the grains are poikiloblastic in nature and show inclusions of associated minerals.

The occurrence of scapolite within these calc-silicate rocks is restricted to the narrow zone around granitic pluton. In a thin section, it can be seen that calcite is being replaced by scapolite, so the reaction of formation of scapolite can be given as,

Calcite + 3 plagioclase = Scapolite, an absence of plagioclase suggests that it might have got consumed completely and that the scapolite is not in equilibrium with calcite and plagioclase (Satish-Kumar et al., 1995),(Fig.4.1k).

Chlorite

Very few samples possess chlorite mineral. It appears as distinct grains as well as in the form of alteration product of biotites. It exhibits colourless to dark green pleochroism and high relief. Tabular crystals are present with good cleavages and straight extinction.

Ankerite

Subhedral to euhedral ankerite can be seen. It shows low relief and extreme birefringence.

Apatite

Apatite grains are present in euhedral form, have high relief and low birefringence and are uniaxial negative.

Zircon

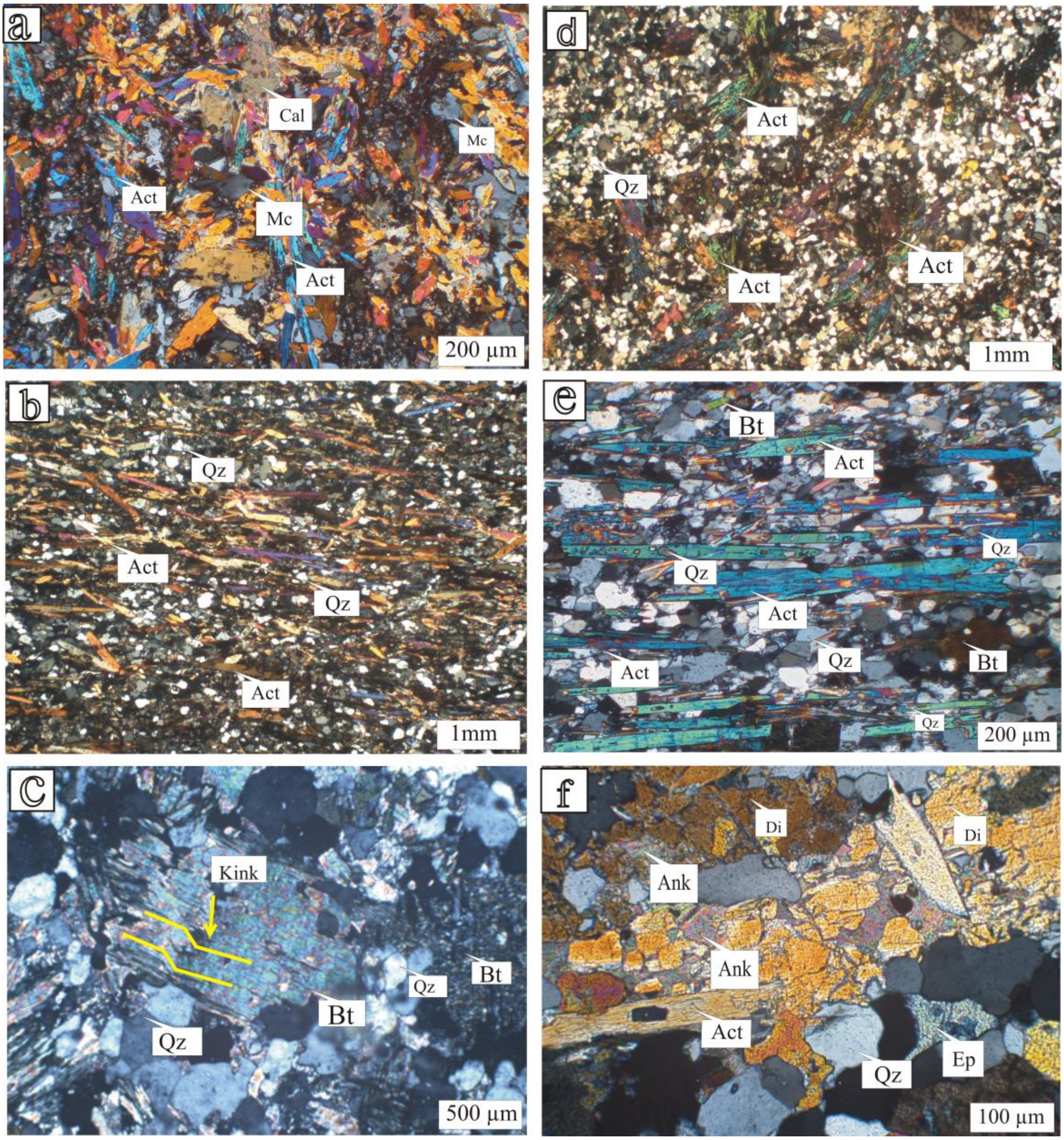
Zircon grains within these rocks are present mostly within biotites and form pleochroic haloes.Good euhedral grains can be seen with high relief and higher order interference colours. Uniaxial positive sign observed.

Ilmenite

An opaque mineral identified within these rocks is an ilmenite. Anhedral granular masses of ilmenite are present. Cleavages are absent. It has an uniaxial negative sign.

At places within these rocks, the mymerkitic texture i.e. the intergrowth of plagioclase feldspar and quartz in presence of alkali feldspar has also been seen. This implies a fluid-induced metasomatic retrograde reaction (Sameera et al., 2015), (Fig.4.1l). The reaction is as follows:

Calcite + alkali feldspar + Na^+ (fluid) = plagioclase feldspar + quartz + K^+ (fluid)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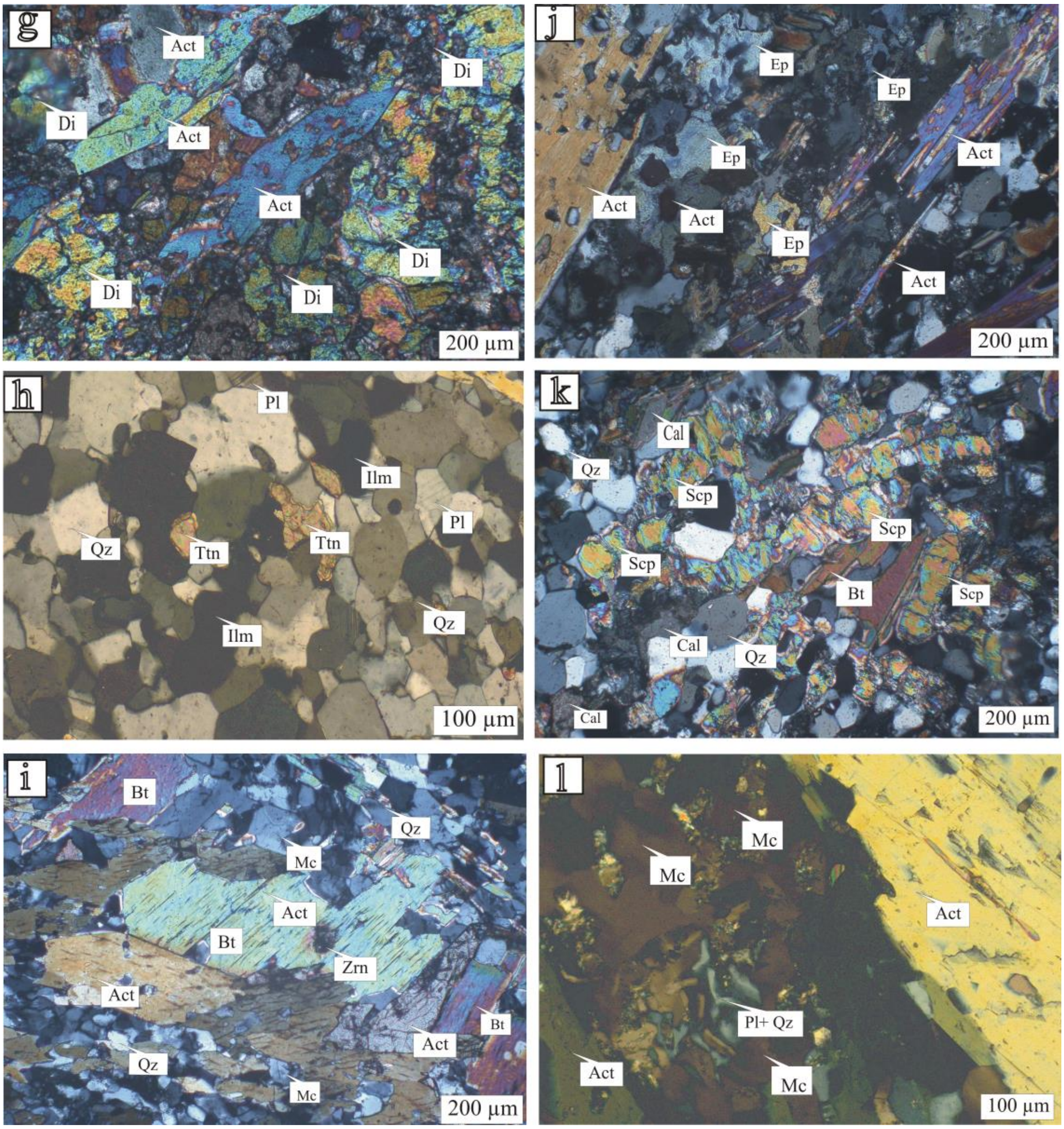


Figure 4.1: Photomicrographs (in crossed polars) of calc-silicate samples showing; a) Hornfelsic texture developed by unoriented actinolites, b) Rarely observed preferred orientation of actinolites, c) Kink seen in biotite porpyroblast ,d) Star shaped actinolites, e) Actinolite porphyroblast with quartz inclusions having concordant relationship with matrix suggesting post tectonic origin of it, f) Replacement of ankeritic mass by salite,g) Actinolite having inclusions of salite suggesting its formation from latter,h) Titanite grains in association with ilmenite and quartz,i) Biotite grain nucleating along the margins of actinolite, j) Epidote grains in association with actinolites, k) Scapolite associated with other minerals like quartz, calcite and biotite, l) Formation of myrmekitic intergrowth.

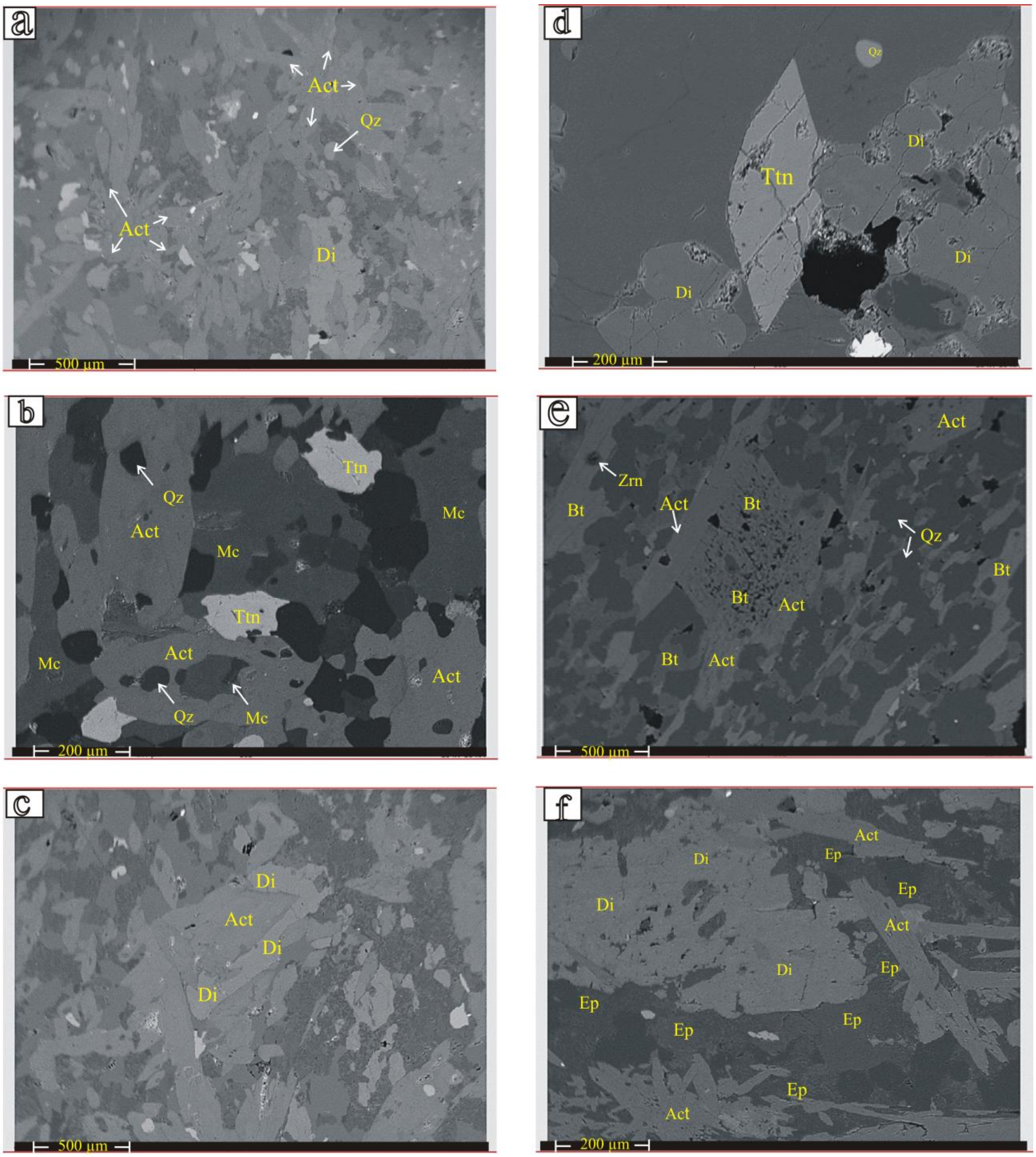


Figure 4.2: Back Scattered Electron images of major and important calc-silicate minerals and reaction textures; a) Star shaped actinolites, b) Poikiloblastic actinolites surrounded by titanite, microcline etc.,c) Replacement of diopside by actinolite,d) Wedge shaped titanite grain, e) Biotite development along edges of actinolites,f) Epidote grains associated with actinolite porphyroblasts.

Table 4.1 Visually-estimated modal amounts of minerals of representative calc-silicate rocks

Sr no.	Sample	Rock	amp	cpx	qz	ttn	cal	kfs	bt	pl	ep	scp	chl	ank	ap	zrn	ilm
1	GA/17/ Ora-03	bt rich Csr	15	-	40	tr	2	3	35	tr	tr	-	2	-	2	tr	1
2	GA/17/ Amlt-05	amp-cpx Csr	35	30	8	2	10	12	3	-	tr	-	tr	-	tr	-	tr
3	GA/17/ Bnm-07	amp-bt-ep Csr	30	8	10	8	5	2	20	-	15	-	tr	-	-	2	-
4	GA/17/ Jnkd-08	amp-bt-ep Csr	32	8	12	8	8	3	15	-	12	-	-	-	tr	2	-
5	GA/17/ Bor-P10	scp bearing Csr	15	tr	10	5	8	10	25	tr	5	20	1	-	tr	1	-
6	GA/18/Jtng-09	amp-cpx Csr	30	25	15	5	4	12	tr	-	7	-	tr	-	2	tr	-
7	GA/18 /Prs-10	amp-cpx Csr	35	25	15	5	2	10	-	-	6	-	1	-	1	-	-
8	GA/18/ Chr-11	amp-ep Csr	30	5	12	5	10	15	tr	-	20	-	3	-	-	tr	-
9	GA/18/ Chr-12	amp-ep Csr	35	5	15	8	8	15	tr	1	12	-	tr	-	1	tr	tr
10	GA/18/ Rgp-13	amp-cpx Csr	35	32	15	8	5	2	tr	-	tr	-	tr	3	-	-	-
11	GA/18 /Tlwd-14	amp-cpx Csr	30	35	8	5	4	15	tr	1	2		tr	-	-	-	-
12	GA/18 /Asnd-17	amp-ep Csr	35	5	10	5	5	8	12	tr	15	-	2	-	tr	2	1
13	GA/18 / Asnd-18	amp-cpx Csr	35	30	12	10	7	4	tr	1	tr	-	1	-	tr	-	tr
14	GA/19/ Rgp-19	amp-cpx Csr	32	35	12	5	8	7	tr	-	tr	-	tr	-	1	tr	-
15	GA/19/Tadi-20	amp-cpx Csr	25	35	10	2	8	10	3	-	5	-	tr	-	1	tr	1

Csr: Calc-silicate rock, tr: present in trace amount < 1%, - not observed, Mineral abbreviations after Whitney and Evans, 2010.

4.2.2 Quartzites

Thin sections of quartzite samples acquired from the study area show that they constitute nearly 85-90% of quartz along with 10-15 % of biotite mica and hence are considered as 'Micaceous quartzites'. Certain microtextures and the grain boundary pattern between quartz crystals depict about the mechanism and phenomenon of deformation and recrystallization.

It has been observed that the samples from different localities of the area comprise of two textural varieties - either the quartz grain boundaries are sutured/serrated and such quartz grains are showing undulose extinction or they are straight thus developing 120º triple junction and exhibit sharp extinction.

The quartz grains within quartzites lying away from the granite have sutured boundaries and show undulose extinction. This condition is possible if the quartz grains are highly strained, i.e. having higher internal energy when they get exposed to the metamorphism followed by deformation at relatively low temperature. According to (Urai et al., 1986 and Passchier and Trouw,2005), the presence of serrated grain boundaries suggests that the rock has undergone 'Grain Boundary Migration' (GBM) recrystallization, this textural feature points towards the higher dislocation density, dynamic recrystallization thus lack of thermodynamic stability and almost an absence of any significant annealing process (Passchier and Trouw, 2005) (Fig.4.3a).

On the other hand, quartzites located closer to the margin of the Godhra Granite show the presence of quartz grains with straight grain boundaries due to which granoblastic polygonal texture is getting developed. Such quartz grains exhibit sharp extinction. This condition results when heat supplied by intrusion releases the strain within quartz grains and makes them thermodynamically stable. Similarly, dislocation density within crystals is also reduced. According to (Ghosh,1985, Passchier and Trouw,2005) such quartz grains must have undergone static recrystallization by 'Grain Boundary Area Reduction' (GBAR) or annealing (Fig.4.3b).

4.2.3 Metapelites

Within the study area mainly biotite schists occur while towards the south of study area garnet mica schists are abundant. The major minerals in the biotite schists are biotite, muscovite, quartz and chlorite. The schistose texture is obvious along with minor porphyroblastic texture. More than one foliation can be seen. S_0, S_1 and S_2 foliations can be identified. S_0 is the primary bedding and appears as the contact between a sheet-silicate rich layer and a sheet-silicate poor layer. Here primary bedding S_0 is almost parallel to the second foliation, i.e. S_1 which is defined by biotite, muscovite and chlorite grains having preferred orientation. The third foliation i.e. S_2 schistosity is defined by biotite laths oriented obliquely to both S_0 and S_1 (Fig.4.3c).

Major minerals of garnet mica schist are garnet,muscovite, biotite and quartz. In this primary bedding (S_0) is almost obscured and the two foliations, viz. S_1 and S_2 are very well developed. Muscovite, biotite and grains of quartz are the main minerals crystallizing along the S_1 foliation while large crystals of biotite and muscovite mark the S_2 foliation. The quartz inclusion trails defining the S_i schistosity within the garnet porphyroblasts are oblique to the external schistosity S_e which implies the syntectonic growth of this garnet during D_2 deformation as according to (Passchier and Trouw, 2005), oblique pattern of porphyroblast or its S_i fabric with respect to S_e is suggestive of the syntectonic origin of that porphyroblast (Fig.4.3d)

4.2.4 Granites

In the nearby region of the study area the Godhra granitic exposures are occurring as two varieties, viz. fine to medium-grained grey granite and coarse-grained pink granite.

Grey granite consists of an abundant amount of plagioclase feldspar along with a quartz, microcline and biotite with accessory tourmaline and opaques. It is holocrystalline with hypidiomorphic texture. Subhedral plagioclases show their typical polysynthetic twinning and grey interference colour. The fracturing of plagioclase can also be seen. These fractures are filled up with other associated minerals like microcline and biotite. They are having lengths ranging from 0.2 to 1 cm. Quartz occurs as interstitial anhedral grains showing wavy extinction. Vermicular quartz grains can be observed due to the development of myrmekitic intergrowth,i.e. the intergrowth of quartz and plagioclase feldspar in association with k-feldspar,viz. microcline. Wavy extinction in quartz and fractures within plagioclases indicate the effects of deformation which might be due to the forceful emplacement of granite. Microcline exhibits polysynthetic tartan twinning and is subhedral. Tabular crystals of biotite show colourless to pale brown pleochroism. Subhedral to euhedral tourmaline grains possess high relief and strong pleochroism from colourless to brown (Fig.4.3e).

Pink granite shows coarse-grained hypidiomorphic texture. Microcline ranges in length from 1 to 1.5 cm while 0.5 to 1 cm in width. Development of myrmekite texture is also seen (Fig.4.3f).

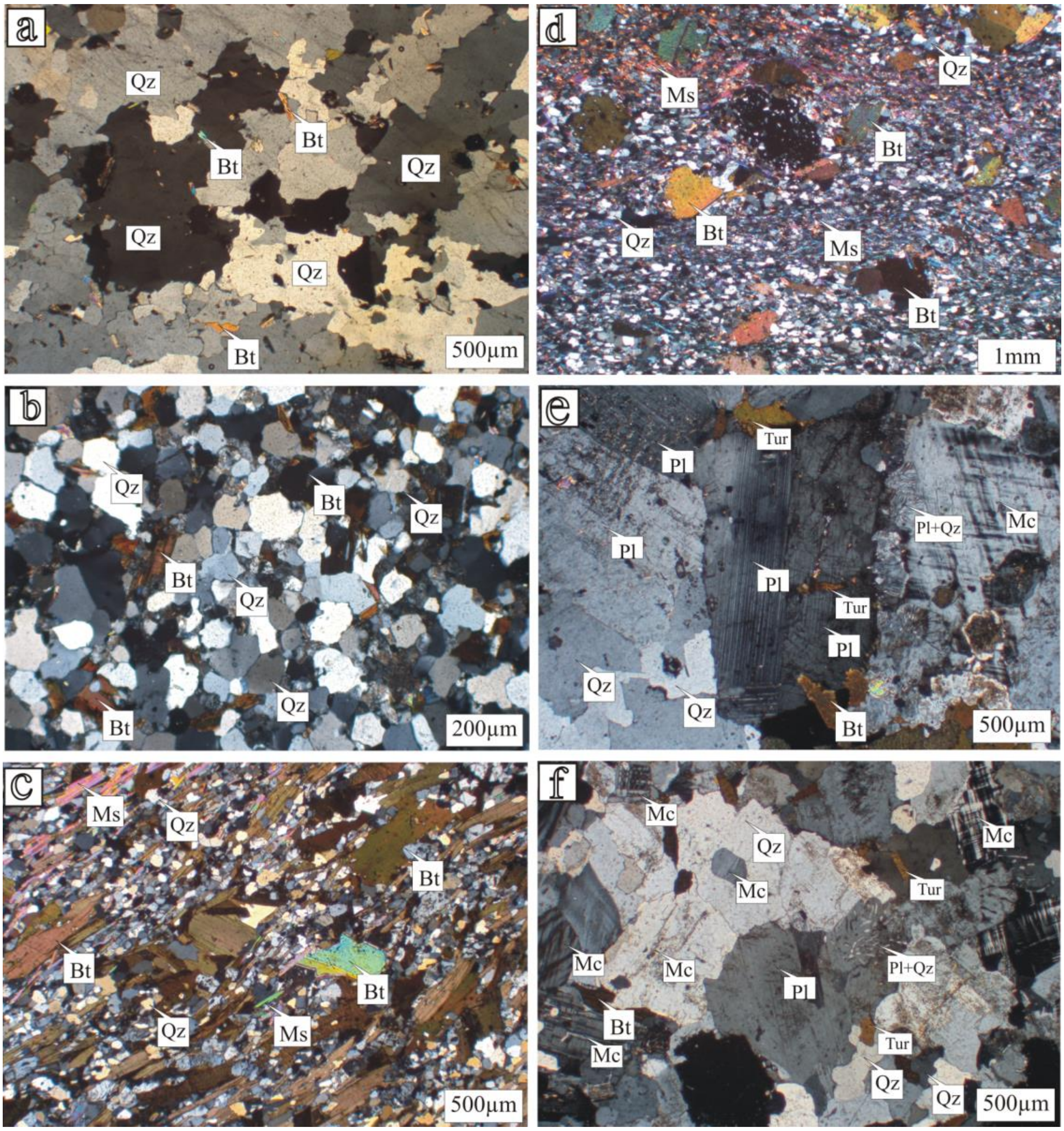
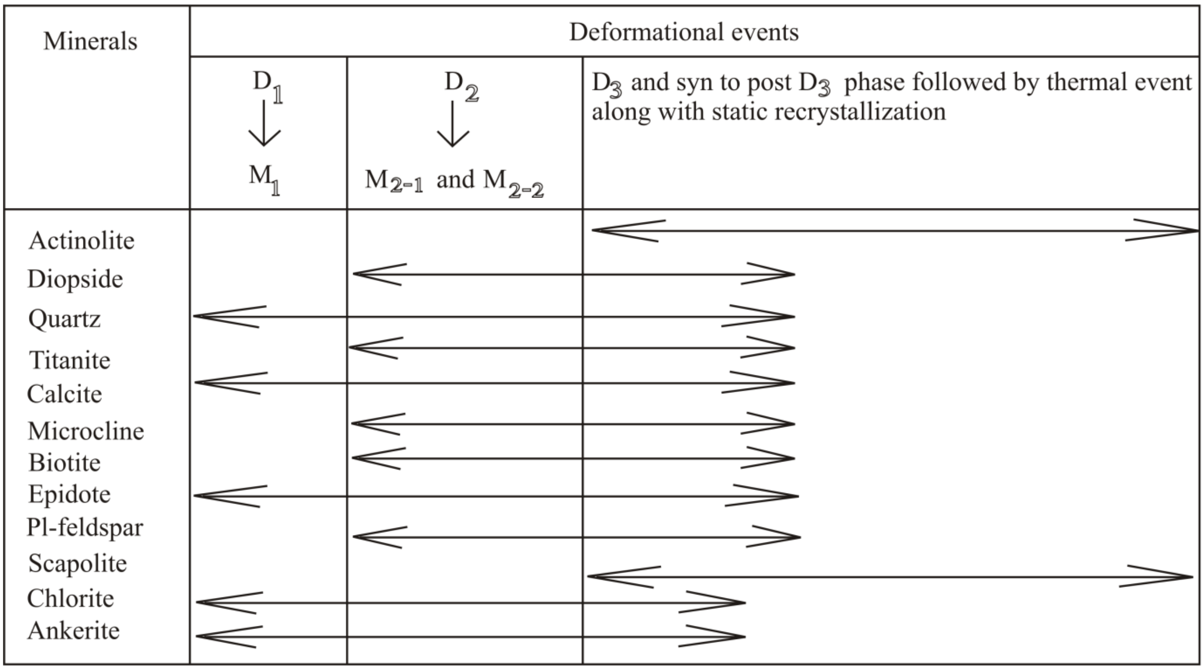


Figure 4.3: Photomicrographs (in crossed polars) showing; a) Serrated quartz grains boundaries within quartzite lying far from intrusion, b) Development of granoblastic polygonal texture can be seen within quartzite lying closer to the intrusion, c) S_1 foliation defined by biotite and muscovite to which bigger porphyroblast of biotite are obliquely aligned forming S_2 foliation plane,d) Inclusion trails within garnet porphyroblast defining internal schistocity (Si) having oblique relation with external schistocity (Se) indicating syntectonic growth of this porphyroblast, e) Fine grained grey granite with abundant plagioclase feldspar biotite and quartz, f) Coarse grained pink granite with abundant microcline and quartz.

4.3 Time relationship between crystallization and deformation

According to Mamtani et al.,(2001), minerals like chlorite (1) and (2) , Biotite (1) and (2), garnet ,muscovite and quartz had been developed in response to the M_1, M_{2-1} and M_{2-2} metamorphism triggered by D_1 and D_2 deformational events in metapelites of Lunavada Group.D_3 phase was feeble with no new mineral formation in metapelites. It has been postulated here, that the minerals appeared during M_1 phase of metamorphism of sedimentary protolith of calc-silicate rocks are quartz, calcite, epidote, chlorite and ankerite while M_{2-1} and M_{2-2} metamorphic phases led to the development of minerals like diopside, titanite, microcline, biotite and plagioclase feldspar. Actinolite and scapolite observed within the calc-silicates are the result of contact metamorphism occurred due to syn to post thermal event of Godhra granite intrusion.

Table 4.2 Development of new minerals within calc-silicate rocks on account of various deformational events followed by syn to post intrusive phase of Godhra granite i.e. a thermal event, (modified after Mamtani et al, 2001)



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