CHAPTER 9. SUMMARY AND CONCLUSIONS

The calc-silicate rocks of the study area around Lunavada had remained one of the most ignored aspects and thus became an enigma for a long period of time. The present study has provided considerable information regarding the petrogenesis of these rocks for the first time, which enables the better understanding of the evolutionary history of the Precambrian shield exposed within the study area which in turn helps to construct the geotectonic model of the evolution of these rocks.

Entire study has been recapitulated and put forward in the form of following points showcasing all important findings.

9.1 Salient findings of the study

- The ‘Kadana Formation’ of the Lunavada Group, a part of the Southern Aravalli Mountain Belt (SAMB) located within the Gujarat state hosts the calc-silicate rocks under study. The Lunavada basin comprises of clastogenic metasediments along with chemogenic as well as biogenic rocks and in the study area quartzite- metapelites intercalations are reported. The calc-silicate rocks occur as discontinuous lensoidal bodies within these intercalations. Plutonic emplacement within this group,i.e.the Godhra granite is rimming its north-west as well as south-east margin. Regional scale folds, viz. F_1, F_2 and F_3 are recorded in and around Lunavada generated on account of D_1, D_2 and D_3 phases of deformation. The calc-silicate rocks exhibit light to dark grey colour and fine to medium grained nature. Prominent field characteristics of these rocks observed include unoriented/star shaped amphibole needles, maculose structure, compositional bandings, differential weathering along with some minor characteristics, i.e. foliations, two sets of joints, presence of structure like convolute bedding, discordant pegmatite veins, boudinages of quartzite and folded quartz vein within them. Field characteristics of quartzites include their major greyish and rare brownish yellow or buff colour, massive as well as compact nature, presence of three sets of joints and plumose markings. Similarly, metapelites exhibit the appearance of chlorite in the northern part, biotite in the central part and garnet in the southern part of the study area. Granites are exposed to the western side of study area in the form of monadnocks, hills, bosses and tors and are massive, fine to coarse-grained, leucocratic to mesocratic and mostly inequigranular. Xenoliths of schists, granite-quartzite contacts, pegmatites within granites with segregated tourmaline crystals and granite - metapelite contacts are some other features observed on the field.

- The calc-silicates are characterised by major hornfelsic/granofelsic texture along with secondary porphyro-poikiloblastic texture and typical mineral assemblage as, act + di + qz + ttn + cal ± mc ± bt ± ep ± pl ± scp ± chl ± ank. The textures and the mineralogy of these rocks are typical of contact metamorphism. As according to (Mamtani et al.,2001), the contact metamorphism due to granitic intrusion was experienced by the rocks of the Lunavada region after regional metamorphism, vague occurrence of regional metamorphic textures is observed in the calc-silicates while contact metamorphic textures are shown by them very prominently. Petrographic studies have identified acicular, bladed, fibrous and sometimes rhombic to pseudohexagonal shaped actinolites which show its typical colourless to pale green pleochroism. Although un-oriented actinolites are common, star shaped and oriented actinolites are also seen within a few samples. Diopside (Salite) shows its typical high relief, weak pleochroism and two sets of cleavages making right angles. It encloses ankeritic mass suggesting its formation from ankerite due to replacement. In some specimens, poikiloblasts of actinolites show inclusions of salite indicating breaking down of salite to actinolite. Titanites occur as both wedge shaped as well as irregular shaped and are often associated with ilmenite. Calcite is present in little amount while microcline is abundantly present. Biotite grains possess colourless to brown pleochroism and can be seen nucleating along the borders of actinolite in association with microcline. Granular aggregates of epidote showing high relief, weak pleochroism and higher order colours can be frequently found in association with actinolite in presence of chlorite. Plagioclase feldspar is present only in few specimens in negligible amount. Scapolite occurs as granular clusters exhibiting moderate relief as well as prominent cleavages. Formation of scapolite is from calcite and plagioclase as observed by replacement of calcite by scapolite but as there is an absence of plagioclase it is concluded that it has got consumed completely. Chlorite appears as distinct grains as well as in the form of alteration product of biotites. It exhibits colourless to dark green pleochroism. Occasionally, mymerkitic texture is also seen within these rock specimens. Quartzites of the study area which are micaceous in nature exhibit two different textural characteristics depending upon their distance from granitic intrusion. The quartz grains within quartzites lying away from the granite have sutured boundaries and show undulose extinction while quartzites located closer to the granite show the presence of quartz grains with straight grain boundaries thus developing granoblastic polygonal texture and exhibiting sharp extinction. Petrography of the biotite schist reveals that S_0 is the primary bedding which 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 oblique to both S_0 and $S_{1.}$ In case of garnet mica schist S_0 is obscured but S_1 and S_2 are very well developed. The quartz inclusions defining the S_i fabric within the garnet porphyroblasts are oblique to the external fabric S_e which implies the syntectonic growth of this garnet during D_2 deformation. Thin section studies of granites show that grey granite variety consists of abundant amount plagioclase feldspar along with quartz, microcline and biotite with accessory tourmaline and opaques and possesses holocrystalline with hypidiomorphic texture while pink granite have abundant microcline and shows coarse grained hypidiomorphic texture. Formation of new minerals within calc-silicates on account of D_1-D_3 phases of deformation and syn to post D_3 granitic intrusion is observed. Actinolite and scapolite mineral development within these rocks is the result of contact metamorphism occurred due to syn to post thermal event.

- Mineral chemistry of all important phases acquired through EPMA reveals that all the amphiboles present in the calc-silicates are calcic as per the nomenclature of Leake (1978) and ranges from magnesio-hornblende to actinolite in composition. X_{Mg} values of magnesio-hornblendes are between 0.66-0.73 while those of actinolites fall within the range 0.75-0.78.Clinopyroxene present within these rocks exhibit a diopside-hedenbergite solid solution with pyroxene components as (Wo_{49-50}, En_{36-39}, Fs_{10-13}). The composition is salitic to diopsidic with X_{Mg} ranging from 0.74 to 0.82. Titanites possess 0.95 -1.02 apfu Ca, 0.81-0.91 apfu Ti, 0.14-0.39 apfu Al and typical titanite has formula as $Ca_{1.02}$ (Ti $_{0.91}Al_{0.19}$ Fe $_{0.006}$) $Si_{0.98}$ ($F_{0.00}$ Cl $_{0.0007}$). Similarly, a representative composition of microcline is $Or_{94.9}Ab_{5.07}An_{0.00}$. Biotites are inclined towards phlogopitic composition with (Fe/ Mg+Fe) ranging from 0.33-0.37 apfu as observed on the Al vs. Fe/(Fe + Mg) diagram of Deer et al. (1992) and also the temperature sensitive Ti content within these rocks increases as the granitic intrusion is approached i.e. from 1.42 to 2.22 wt%. Epidotes are rich in Fe^{3+} and all epidote analyses contain 2.28-3.18 apfu Si, 2.34-2.54 apfu Al^{tot}, 1.98-2.03 apfu Ca. Plagioclase feldspars show wide range in composition i.e. from oligoclase to labradorite on the An-Ab-Or ternary diagram. Scapolites are Cl-absent calcic-rich meionites and meionite component varies from 93.7 to 99.8%. Chlorite composition varies from pycnochlorite to clinochlore as observed on the classification diagram of Hey (1954). Apatite contains 5.65-5.75 apfu P, 9.60-9.82 apfu Ca and 0.005-0.085 apfu Si and ilmenite possesses 2.005-2.034 apfu Ti and 1.88 apfu Fe. All this data points towards the impure calcareous sediments as a protolith for calc-silicate rocks.

- Major, trace and REE compositions of the calc-silicates derived through the geochemical analyses and the data was plotted on binary or ternary diagrams. As they belong to the Meso-Proterozoic supracrustals of the Lunavada Group, all major, trace and REE compositions of these rocks are comparable with PAUCC. SiO_2 is positively correlated Al_2O_3, Na_2O, K_2O and TiO_2 whereas inverse correlation is present between SiO_2 and CaO, MgO, FeO, MnO, P_2O_5 and LOI as shown by Harker plots. LREE-enriched but HREE-depleted subparallel chondrite-normalized REE patterns with moderately negative Eu anomalies exhibited by these rocks is the perfect condition of post-archean sedimentary protolith. Immobile elements like HREEs, HFSEs, Cr, Co, Th and Sc are used to find out protolith, provenance and tectonic setting of the sedimentary protolith. Very few calc-silicate samples fall within the marl zone and most of them fall within the greywacke zone as observed on the CaO, Al_2O_3 and FeO + MgO ternary diagram indicating the presence of both quartzo-feldspathic and clayey material within protolith. Positive correlation observed between Al_2O_3 and most of the trace elements along with Na_2O and K_2O is also suggestive of protolith which is bound to clay minerals. High amount of sedimentation and recycling led to the higher amount of Zr and Ba, thus these elements have positive correlation with SiO_2. Ba is positive correlated with K_2O also indicating felsic nature of source. On the sandstone-shale continuum within Al-Zr-Ti diagram, a near linear variation of calc-silicate samples is seen with these samples inclined more towards sandstone than shale. This is thus one more evidence of presence quartzo-feldspathic material with little and varied amount of clay. It is, therefore, concluded that the protolith of present day calc-silicates is calcareous sandstone with some clayey impurities. Chemical Index of Alteration (CIA) values for calc-silicate rocks are low to moderate i.e. 50 to 86 with average = 68 as observed on the conventional Al_2O_3 - (CaO+Na_2O) - K_2O (A – CN – K) ternary diagram. Moderate degree of alteration is indicated as most of the samples fall closer to illite. Low CIA values indicate either cold and/or arid conditions or rapid physical weathering in subtropical conditions with almost no chemical alteration. These calc-silicates have Th/Sc > 1 and Zr/Sc > 10 as observed on Th/Sc-Zr/Sc plot. Values of Th/Sc > 0.79 indicate felsic source and Zr/Sc ratio for these rocks indicates good amount of sorting and recycling of sediments. These rocks are rich in incompatible elements like Th, Zr and La supporting the felsic nature of their provenance while they are depleted in compatible elements like Sc, Cr and Co which are abundant in rocks having mafic provenance. On Th/Co and La/Sc plot also, these rocks fall within the felsic composition. Deposition of sedimentary rocks or protolith of these calc-silicates took place within active continental margin settings as shown by Sc-Th-Zr/10 diagram.

- Temperature at peak metamorphism for calc-silicates is estimated using single mineral thermometer i.e. Ti-in-biotite thermometer of Henry et al.(2005). It works on the perception that with the increase in temperature, the Ti content in magnesian biotites also increases.The thermometer is empirically calibrated for biotites equilibrated over a temperature range of 480-800ºC and 4-6 kbar pressures, having compositions of Mg/(Mg+Fe) between 0.275 and 1.000 and Ti = 0.04-0.60 apfu. Temperature estimate from core and rim analyses of the two biotite grains within the calc-silicate sample located away from granite and that from the calc-silicate sample located near to granite ranges from 618-649 ± 24ºC (i.e. the with the difference of 31ºC) averaging at 618 ± 24ºC in the cores, and 614 ±24 ºC in the rims. An average temperature, 634ºC is estimated at peak metamorphism. Pressure value at peak metamorphism of calc-silicates is calculated with the help of Silica-Ca-tschermak's-anorthite barometer as these rocks are free of garnet. In pressure-sensitive equilibria involving only pyroxene, plagioclase and quartz, the aluminous components in pyroxene is balanced by the aluminium component in plagioclase. The equation, $P = \frac{6.330\,[\pm 0.116] - \ln K}{301[\pm 9]}\,.\,T\,[\pm 1.0\ \text{kbar}]$ is used for pressure estimation which is derived through least square regression analysis of experimental data from the partial melting experiments of natural phases as well as from the phase equilibrium experiments on the end-member CMAS system. Mole fractions and ideal activity expressions were calculated for Ca-tschermak and anorthite component and then putting the values in above equation the pressure at peak metamorphism of calc-silicates calculated is 1.1 kbar. Phase diagrams or pseudosections were constructed with the help of Perple_X software, version 6.8.1.Holland and Powell thermodynamic dataset (2003) was used and isobaric T-X(CO_2) pseudosections were modelled in the system: K_2O-Na_2O-CaO-MgO-FeO-TiO_2-Al_2O_3-SiO_2-H_2O-CO_2 (KNCFMASTCH) to acquire the stability field for observed equilibrium assemblage within a rock sample. Fluid compositions range assumed between 0 and 1 for X(CO_2) and pressure as 1kbar as these calc-silicates reside within the contact aureole developed within study area. As an example for pseudosection calculations a calc-silicate sample, viz. Ora-03 is considered. In its pseudosection, calcic amphibole and cpx are in equilibrium within the assemblage observed as 'amph pl pl cpx fa osm1 sa ilm' which derived the stability field with temperature range of 500°-560°C and fluid compositions of X(CO_2) >0.90. Calcic amphibole (actinolite) appears at almost 380°C and destabilizes above 470°C with the appearance of cpx (diopside) which defines the minimum temperature required for its formation and at X(CO_2) range = 0.9 to 1. Chemical compositions of minerals and rocks portrayed by chemographic projections assist in phase equlibria studies. These diagrams show that the appearance of phases like talc, tremolite and diopside is observed with the progression of metamorphism of protolith,i.e. calcareous sandstone with the major assemblage as Dol + Cal + Qz. 'Hornblende-hornfels facies' of contact metamorphism is concluded from overall metamorphic conditions of these rocks. The active continental margin setting of the calc-silicates and their Mesoproterozoic age is vindicated by the depositional history of the Aravalli supergroup from passive margin to active margin towards the middle phase of the Aravalli Geological Cycle. Various stages depicting the tectonic evolution of Lunavada basin had been explained via plate tectonic model of the evolution of the Aravalli fold belt. At about 1.83 Ga, rifting started which led to the opening of Aravalli basin followed by passive margin stage at 1.77 Ga. It was accompanied by the deposition of carbonates and phosphorites in shallow water along with deposition of carbonaceous shales in deeper water. During a time frame, i.e. 1.64-1.59 Ga, an active margin stage was designated by the beginning of accretionary orogenesis with the eastward subduction of oceanic crust. At around 1.59 Ga, the process of crustal extension generated a back arc basin i.e. the Lunavada basin which later intruded by associated continental arc pluton (Granite) causing the thermal metamorphism of protolith of the present day calc-silicates.

- Comparative petrogenetic studies of calc-silicates of Lunavada region was carried out with those from other parts of SAMB lying within the Gujarat which include the

Champaner region mainly as in the remaining areas only dolomitic rocks are present.The Champaner Group which is a youngest group of the Aravalli Supergroup is located at the south-western part of Lunavada Group and is also intruded by Godhra granite.The calc-silicate rocks of this group reside within the ‘Khandia Formation. A cyclic sequence of phyllite, quartzite and meta-conglomerate with lenses of dolomitic limestone is observed within this group.It has also experienced D_1-D_3 deformational phases resulting into F_1-F_3 folds. The calc-silicates of this group are fine to medium grained and mainly greyish coloured. Unoriented amphibole needles, elephant skin weathering, foliations and few calc-silicates having greenish colour are the megascopic characteristics observed. Petrographic analysis revealed the prominent hornfelsic texture along with minor porphyro-poikiloblastic texture. These rocks possess about 60-70 % of dolomitic matrix as compared to the calc-silicates of the study area around Lunavada which possess less than 5% volume of carbonate minerals (calcite/ankerite). The mineral assemblage observed within these rocks is dol + tr + di + scp + ttn + tlc + qz ± cal ± grt ± chl ± pl ± mc along with minor proportion of opaques. As per the mineral chemistry studies, the amphiboles of the calc-silicates from Champaner are calcic and having tremolitic composition with X_{Mg} values between 0.94-0.96 as compared to those from the calc-silicates of Lunavada where chemical composition varies from magnesio-hornblende to actinolite. The clino-pyroxene of calc-silicates is totally diopsidic in case of Champaner region whereas the Cpx of rocks from Lunavada makes them more salitic. The meionite component of scapolite of Champaner ranges from 99.6 to 99.7% whereas that of Lunavada ranges from 93.7 to 99.8% and the chlorite composition of calc-silicates of Champaner ranges from sheridanite to chlorite while it shows compositional range from pycnochlorite to clinochlore in case of calc-silicates of Lunavada. Major, trace and REE compositions of calc-silicates of Champaner area acquired by geochemical analyses and compared with those of PAUCC compositions. The Harker plots show positive correlation of SiO_2 with Al_2O_3, Na_2O, K_2O, TiO_2, CaO, FeO and MnO whereas negative correlation with MgO only. The calc-silicates of Champaner exhibit LREE-enriched but HREE-depleted subparallel chondrite-normalized REE patterns with slight negative Eu anomalies (Eu/Eu*) ranging from 0.7 to 0.9 in contrast to the rock samples of Lunavada which show moderately negative Eu anomalies, ranging from 0.5 to 0.7. The protolith of calc-silicates from champaner area is siliceous dolomites i.e. dolomites having quartzo-felspathic and clayey impurities in contrast to the calcareous sandstone as a protolith for calc-silicates of Lunavada. Mafic nature of provenance is indicated for the calc-silicates of Champaner due to Th/Sc ratio < 0.79, low Zr/Sc ratio and enrichment in compatible elements like Sc, Cr and Co as compared to the calc-silicates of Lunavada which exhibit felsic nature of provenance. Moreover, the calc-silicate samples of the Champaner fall in an array indicative of mafic composition of the source rocks on the Th/Co vs. La/Sc bivariate plot. Tectonic settings in which sediments were deposited in case of calc-silicates of Champaner vary from continental island arc to active continental margin in contrast to the Lunavada rocks where sediments deposited at the active continental margin only. Standard 1kbar pressure is considered for the calc-silicates of the Champaner at peak metamorphism as they lie within the well-defined contact aureole and because of the lack of suitable thermometer, based on petrographic studies, temperature is assumed to be between 650° to 700°C.Phase diagrams or pseudosections were constructed with the help of Perple_X software,version 6.8.1. Holland and Powell thermodynamic dataset (2003) was used and pseudosections were modelled in the system:K_2O-Na_2O-CaO-MgO-FeO-TiO_2-Al_2O_3-SiO_2-H_2O-CO_2(KNCFMASTCH).Fluid compositions range assumed between 0 and 1 for X(CO_2).As an example for pseudosection calculations, a calc-silicate sample, viz. Gndh-06 is considered. Using whole rock geochemistry the equilibrium assemblage, dol+ tr +di + scp + ttn + tlc +qz + mc which was observed in thin-section of (Gndh-06) sample, used in pseudosection calculations. In its pseudosection, calcic amphibole, cpx and titanite are in equilibrium within the assemblage observed as ’amph cpx fo ttn phl nph cal ’ which derived the stability field with temperature range of 610°-680°C and fluid compositions of X(CO_2) < 0.95. The pressure and temperature conditions at peak metamorphism indicate metamorphic facies as ‘Pyroxene-hornfels facies’ of contact metamorphism and is supported by phase equilibria studies also.

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