Synopsis of the Ph.D. thesis entitled

Tectono-metamorphic evolution of Calc-silicate rocks around Lunavada, Gujarat.

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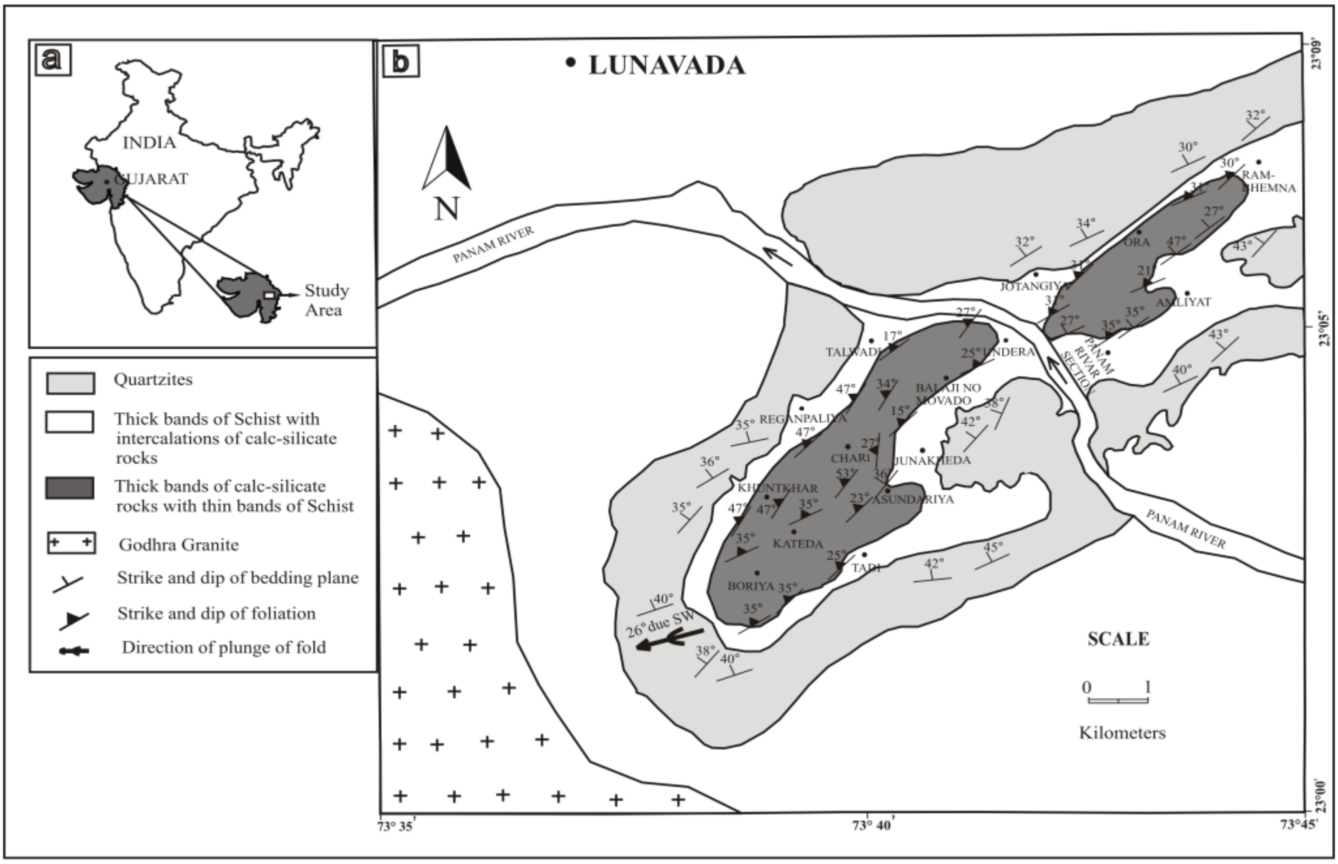
INTRODUCTION

Calc-silicate rocks are medium to high grade metamorphic rocks consisting essentially of calc-silicate minerals and less than 5% volume of carbonate minerals i.e. calcite and/or aragonite and/or dolomite), as per the 'Subcommission on the Systematics of Metamorphic Rocks' (SCMR) classification scheme. These rocks are reported to occur as small scattered outcrops or isolated lensoidal bodies amidst Precambrian rock formations throughout the shield area of Peninsular India. The Calc-silicates being studied here belong to the Lunavada Group, exposed in NE Gujarat, is a second youngest Group of the Aravalli Supergroup and identified as a part of Southern Aravalli Mountain Belt (SAMB).These rocks comprise youngest formation of Lunavada Group known as 'Kadana Formation' having Meso-proterozoic age and are geographically located at the NE part of the Gujarat state. It is the only formation of Lunavada Group, some part of which falls within Gujarat unlike remaining formations which completely fall within Rajasthan.

Chief rock-types of the Lunavada Group are metapelites, quartzites, meta-subgreywackes, petromict meta-conglomerates with minor layers of marble and phosphatic algal meta-dolomites (Gupta et al., 1980; 1992; 1995; 1997). The Lunavada Group of rocks mark the polygonal shaped outline, which occupies an area of more than 10,000 sq km. The said lithological sequences are invaded by Neo-Proterozoic Godhra intrusives of 955 ± 20 Ma. (Gopalan et al.,1979).The grade of regional metamorphism has reached up to lower amphibolite facies condition by the development of chlorite grade in the northern part to garnet grade in the southern part within the schistose rocks of the Lunavada terrain (Mamtani, 1998; Mamtani et. al., 2001).

Structurally, rocks of the Lunavada region are affected by three deformational episodes. D_1 and D_2 are coaxial with NE-SW striking axial traces, whereas D_3 marks the NW-SE trend and is coeval with the granite emplacement (Mamtani et al., 2001; Mamtani and Greiling, 2005; Mamtani et. al., 2002; Sen and Mamtani, 2006). Several NW-SE trending axial planer slippages have also been recorded with the last phase of deformation (Mamtani et. al., 1999a; Joshi et. al., 2016). The area selected for the study lies towards the SE of Lunavada town, which comprises intercalated sequence of quartzite-metapelite with minor bands and lenses of calc-silicate rocks (Fig. 1).



(modified after Mamtani 1998)

(**Fig.1.** Location and geological map)

Lithological aspects of the southern most parts of Rajasthan and northern parts of Gujarat were worked out by Gupta and Mukherjee (1938), they prepared an excellent geological map of this area. A detailed account of stratigraphic, sedimentational, deformational and metamorphic history of the Proterozoic sequence exposed in the Kadana reservoir and adjacent areas has been given by Iqbaluddin (1989) and structural geology studies with respect to fold history, deformational mechanisms along with related metamorphic aspects have been carried out by (Mamtani 1998) and although few investigators like Iqbaluddin(1989) and Mamtani (1998) have mentioned the occurrence of calc-silicate rocks in and around area, a clear understanding of the origin and the metamorphic history of the rocks, which is essential for a correct interpretation of a geotectonic model for the evolution of these rocks is still lacking. Thus it is a least understood crustal sector in terms of this aspect. Hence present author has taken up the problem 'Tectono-metamorphic evolution of calc-silicate rocks'. For this purpose field investigation was carried out of an around 80 sq. km area near Lunavada town, Mahisagar district, Gujarat (Survey of India Topographic Sheet No. 46 E/12).

RESEARCH OBJECTIVES:

- To determine the protolith/parent rock of the calc-silicates of the study area.
- To interpret the evolutionary history of these calc-silicate rocks by understanding their petrogenesis.
- To perform the comparative petrological studies of calc-silicate rocks from other parts of Southern Aravalli Mountain Belt (SAMB).

METHODODLOGY:

- Geological mapping of Calc-silicate rocks was carried out.
- Detailed sampling of Calc-silicate rocks was carried out for whole /bulk rock geochemistry.
- Thin sections were prepared for petrographic analysis.
- Special thin sections were prepared for the determination of chemistry of various minerals in these rocks which was obtained by the EPMA studies.
- Bulk rock geochemistry was obtained by XRF, HR-ICP-MS instrument. Geothermo-barometry of samples was done.
- Phase diagrams were computed as a function of calc-silicate whole rock composition.
- Metamorphic facies of calc-silicate rocks was determined.
- Studies related to the evolution of southern part of the Aravalli basin on the basis of geochemistry of these rocks are under process .

Results and Discussions:

The methodologies applied above helped to generate the clear picture regarding petrogenesis of calc-silicates of the study area thereby achieving the proposed research objectives. The results obtained have been discussed below:

To determine the protolith/parent rock of the calc-silicates of the study area:

Megascopic characterisics of these calc-silicates include their fine to medium grained nature, light to dark grey colour, star shaped or unoriented actinolite needles as well as the maculose structure. Apart from this, minor features observed within these rocks are the compositional bandings and foliations.

To achieve the abovesaid objective, petrographic studies of over fourty calc-silicate samples carried out which revealed their prominent granofelsic/hornfelsic texture as well as characteristic assemblage as, actinolite + diopside + quartz + titanite + calcite ± microcline ± biotite ± plagioclase feldspar ± epidote ± scapolite ± chlorite along with minor apatite, zircon and opaques. This assemblage itself indicates the calcareous parent rocks having some impurities of siliceous as well as argillaceous material within them. Moreover, the mineral chemistry which offered the accurate composition of minerals of these rocks, e.g. Ca-amphibole and clinopyroxene are Fe rich ,i.e actinolite and salite, respectively, mica is phlogopitic biotite (i.e. with some Mg content), similarly scapolite, here is a Ca-rich meionite , indicate calcareous protolith with clayey impurities. Inferences drawn from the whole rock geochemistry of these rocks provides the exact protolith type. For this purpose the geochemical analysis (major, trace and REE compositions) of seventeen representative samples of the calc-silicate rocks of study area was carried out.

Whole Rock Geochemistry

Major and trace elements compositions:

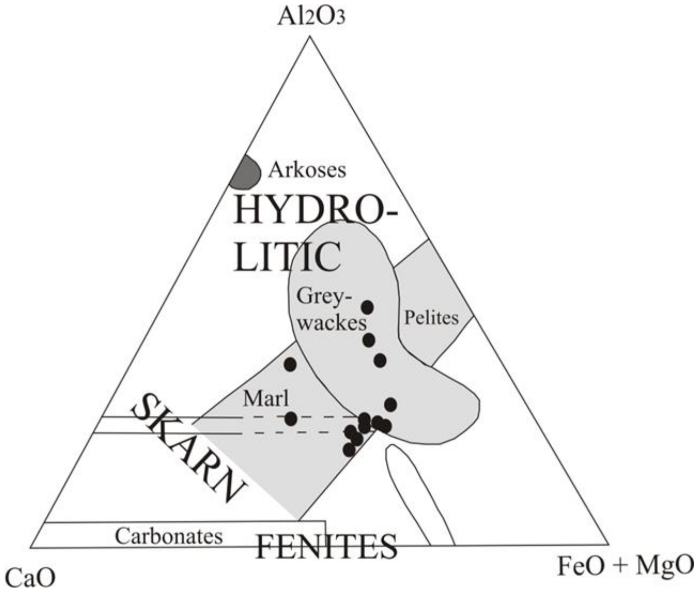
Analysed calc-silicate rocks exhibit a range of SiO_2 (51.4-64.9 wt.%) and Al_2O_3 (7.8-13.1 wt.%) which is lower than the average composition of post-archean upper continental crust (PAUCC), i.e 65.9% and 15.17% respectively of Taylor and Mclennan (1985) whereas MgO (5.7-15.6 wt.%),CaO (5.4-13.5 wt.%),FeO (3.7-6.9 wt.%), and MnO (0.1-0.4 wt.%) whole-rock compositions show enrichment relative to the compositions of PAUCC.

Analysed calc-silicates show concentrations of Zn(61-91 ppm), Ga(27.6-50.2 ppm) and large-ion-lithophile elements (LILEs) viz. Rb(101.4-1547.7 ppm), Ba(156-2076 ppm) and Th (26.2-66.5 ppm) and high field strength elements (HFSEs) viz. Zr (150.9-467.8 ppm), Nb (15.9-29.8 ppm) Hf (5.1-15.0 ppm) which are higher compared to the PAUCC whereas they are generally depleted in V(35 -74 ppm), Cr (41-73 ppm),Ni (24.5-33.5 ppm),Cu (10.2-29.3 ppm) along with other LILEs i.e. Sr (90.1-206.3 ppm) and U(0.9-3.0 ppm). Similarly, analyzed calc-silicates have concentrations of Co (10.6-24.4 ppm), another LILEs such as Cs (0.50-11.03 ppm), Pb (14.0-29.1 ppm) and another HFSE viz.Ta (0.7-1.4 ppm) similar to PAUCC.

Protolith of calc-silicate rocks

Certain alterations or metamorphic events affect the mobility of some elements such as Si, Na, K, Ca, Mg, Rb, and Sr of parent material of metamorphic rocks like calc-silicates. Hence relatively immobile elements such as the HREEs, HFSEs, Cr, Co, Th and Sc can be considered most reliable for protolith determination (Taylor and McLennan 1985; Bhatia and Crook 1986) as they generally pass on to the sediments quite unfractionated during sedimentary processes thus leaving the signatures of parent material within those sediments (Nance and Taylor 1977; Taylor and McLennan 1985; McDaniel et al. 1994).

Relative proportions of major-elements such as SiO_2, CaO, Al_2O_3, FeO, and MgO reveal whether the calc-silicates possess a carbonate/silicate-rich clastic protoliths or metasomatic origins (Barton et al. 1991; Tracey and Frost 1991). Calc-silicate bulk-rock compositions normalized to CaO, Al_2O_3, and FeO + MgO correspond closely to the compositions of marls and calcareous sandstone (Pettijohn 1984). On CaO, Al_2O_3 and FeO + MgO ternary diagram, most of the calc-silicate samples fall within or very near to greywacke zone (Fig.2).



(**Fig.2**. CaO-Al_2O_3-FeO+MgO (wt. %) ternary diagram showing bulk rock compositions of Calc-silicate rocks. Unaltered arkoses, pelites, greywackes and marls are represented by shaded fields along with schematic regions for metasomatic types (after Barton et al.1991).

The negative correlation of CaO, MgO, FeO, MnO, P_2O_5 and LOI with SiO_2 observed within sample areas may therefore be due to quartz dilution related to variable amounts of quartzo-feldspathic material and clay within protolith, also the positive correlation of Al_2O_3 with nearly all measured trace elements as well as with Na_2O and K_2O indicates that the K-bearing minerals exert significant control over the Al distribution thus further suggesting that the protolith must had been bound to clay (McLennan et al. 1990; Condie et al. 2001).

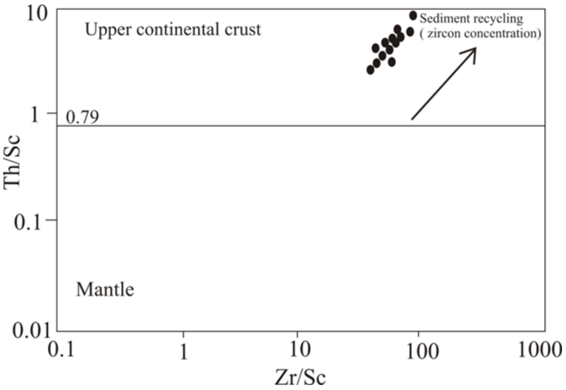
These facts implies that the protolith of calc-silicates is calcareous sandstone having little amount of clay.

To interpret the metamorphic or evolutionary history of these calc-silicate rocks by understanding their petrogenesis

The studies carried out regarding provenance/source area, tectonic conditions as well as metamorphic conditions facilitated the building up of evolutionary history of these rocks.

Provenance and tectonic setting

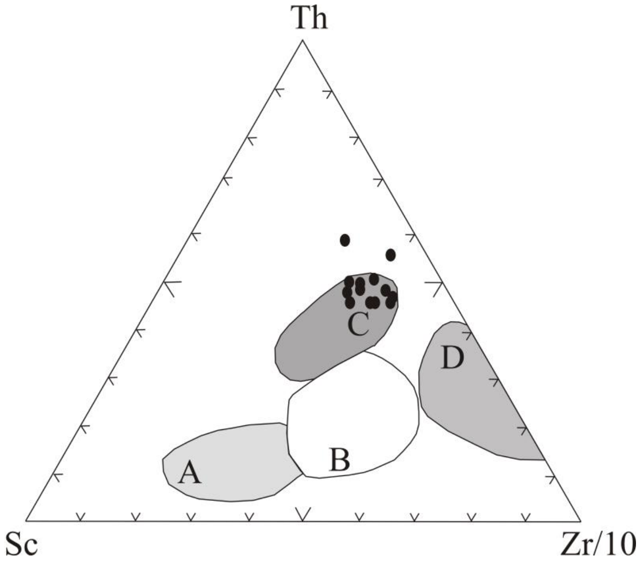
Apart from the purpose of protolith determination, immobile elements like Zr,Ti,Y,Nb,Cr,Sc,La,Th,Ce and Nd are often used to infer the paleo-tectonic environments of metamorphic rocks (Nutman et al.2010; Giere et al.2011). The Th/Sc–Zr/Sc plot (Fig.3) can distinguish between evolved and juvenile sediment sources and the extent of sorting and recycling experienced by sediments (Taylor and McLennan 1985; McLennan et al. 1990). Higher Th/Sc, i.e. (≥1) and Zr/Sc (≥10) values represent sediments derived from evolved continental sediment sources relative to sediments from juvenile, mafic sources (Roser et al.1996).



(**Fig.3.** Th/Sc vs Zr/Sc ratio diagram showing the composition of the sources for the primary sediments of calc-silicate rocks and the extent of recycling or concentration of Zr in sediments (after McLennan et al.1990).

Th/Sc ratio, here, is greater than 0.79 which indicates that these calc-silicate rocks evolved through the provenance from a felsic source. Also these rocks are enriched in elements like Th, Zr and La which again supports the detritus from felsic source. Trace element studies revealed that the source of these calc-silicates was similar in composition to the average post-archean upper continental crust, mostly granitic thus supporting an idea that a significant amount of differentiated felsic igneous rocks probably present in the source area at the onset of sedimentation.

Geochemistry of sedimentary rocks (protolith) is affected by conditions due to associated tectonic setting also, to large extent (Bhatia and Crook 1986; Roser and Korsch, 1986; McLennan et al. 1990).Here, it can be seen that the sample data are plotted within the field of active continental margin of Sc- Th- Zr/10 plot of Bhatia and Crook (1986), (Fig.4). Deposited sediments at the active continental margin are poorly sorted, less recycled as well as are having less maturity than those deposited at the passive continental margin (Roser et al.1996).



(**Fig.4.**Sc-Th-Zr/10 diagram of Bhatia and Crook (1986). A: oceanic island arc; B: continental island arc; C: active continental margin D: passive/rifted margins)

Determination of metamorphic conditions of calc-silicates

For this purpose, the conventional geothermo-barometry as well as pseudosections were implemented. Ti-in-Biotite thermometer of Henry et al.(2005) was used for temperature estimation at peak metamorphism. It works on the concept that as the temperature increases, the Ti concentration in magnesian biotites also increases. The expression of this nonlinear trend is:

$$T = \{[\ln(Ti) - a - c(X_{Mg})^3]/b\}^{0.333},$$

where T is the temperature in ºC, Ti is the apfu normalized to 22 oxygen atoms, X_{Mg} is Mg/(Mg+Fe), and a, b, and c are parameters or surface-fit equation coefficients that represent the fit of the Ti concentration in biotites. Their values are, a = -2.3594, b= 4.6482×10^{-9} and c = -1.7283.

Here, temperature estimates from Titanium–in–Biotite thermometry were obtained from core and rim analyses on two biotite grains from the sample present away from granitic contact and two biotite grains from the sample near to the granitic contact. Biotites selected for this study were free of inclusions, showed no retrogression. All analyzed biotites meet the compositional criteria recommended for use of the thermometer. Averages of core and rim compositions were employed in calculations.

Biotite compositions result in a temperature range of 570-600 ± 20ºC averaging at 600 ± 20ºC in the cores, and 590 ±20 ºC in the rims.

For certain rocks like these calc-silicates under study which lack garnet, pressure estimation become possible by SCAn barometer as such type of rocks contain atleast contain pyroxene, plagioclase and quartz (Newton and Perkins, 1982).

According to (McCarthy and Patino Douce,1998),in order to formulate pressure-sensitive equilibria involving only pyroxene, plagioclase and quartz, the aluminous components in pyroxene (the Ca-tschermak component) has been utilised to balance the aluminium component in plagioclase. The pressure-sensitive equilibrium among anorthite, quartz and the Ca-tschermak component in clinopyroxene ($CaAl_2SiO_6$; CaTs),

$$CaAl_2SiO_6^{Cpx}+SiO_2^{Qtz} = CaAl_2Si_2O_8^{Pl}$$

can be used as a geobarometer in granulites with the proper assemblage.

Linear least-squares regression analysis of the experimental data resulted in the following empirical expressions for pressure in terms of composition and temperature:

$$P = \frac{5.066\,[\pm 0.760] + \left(\frac{1300\,[\pm 800]}{T}\right) - \ln K\,.T\,[\pm 2.5\text{ kbar}]}{276\,[\pm 16]}$$

Or

$$P = \frac{6.330[\pm 0.116] - \ln K\,.\,T\,[\pm 1.0\text{kbar}]}{301[\pm 9]}$$

Where,

$$K = \frac{a_{An}^{Pl}}{a_{CaTs}^{\ Cpx}}$$

Here, second equation is used for pressure calculation as it is more accurate than first although it is not utilising enthalpy term like first one. The reaction in which quartz and Ca-tschermak component of clinopyroxene combine to form anorthite,

$CaAl_2SiO_6^{Cpx}+ SiO_2^{Qtz} = CaAl_2Si_2O_8^{P}$,fixes the chemical potential of Ca-tschermak component and has been studied experimentally by Hays (1966), Hariya & Kennedy (1968), Wood (1976, 1978, 1979) and Gasparik (1984a,b, 1986). On the basis of representative Clinopyroxene (Ca-tschermak component) and plagioclase analyses, the calculations for mole fractions and ideal activity expression have been carried out by using the following formulae:

Mole fractions and ideal activity expression for CaTs and An:

Clinopyroxene activity–composition relationships (Wood, 1979)

Cation assignment [recalculated on the basis of 6(O)]

$Al^{iv} = 2\text{-}Si$, $X\ Al^{M1} = Al\text{-}Al^{iv}$, $X\ Ca^{M2} = Ca$, $X\ Si^{iv} = Si/2$, $X\ Al^{iv} = (2\text{-}Si\ )/2$

$a_{CaTs}{}^{Cpx} = 4\ XCa^{M2}\ XAl^{M1}\ XAl^{iv}\ XSi^{iv}$

Plagioclase activity–composition relationships (Holland & Powell, 1992)

$X_{An}= Ca/(Ca+Na+K)$, $X_b = 0.12+0.00038\ T$,$X_{An,c} = X_{An}\ (1+X_{An})^2\cdot 1/4$,$I_{An}= -RT\ \ln\ (X_{An,c}/X_{An})\text{-}(W_c\text{-}W_i)\ (1\text{-}X_b)^2$,$W_c = 1070.0\ J\ mol^{-1}$,$W_i = 9790.0\ J\ mol^{-1}$

$\mathbf{a_{An,c}{}^{Pl}} =X_{An,c}\ \exp\ (1/RT\ [W_c\ (1\text{-}X_{An})^2+I_{An}])$

Putting the values of respective cations in above formulas, the pressure estimated for the calc-silicate rocks of Lunavada region is **0.88 Kbar**

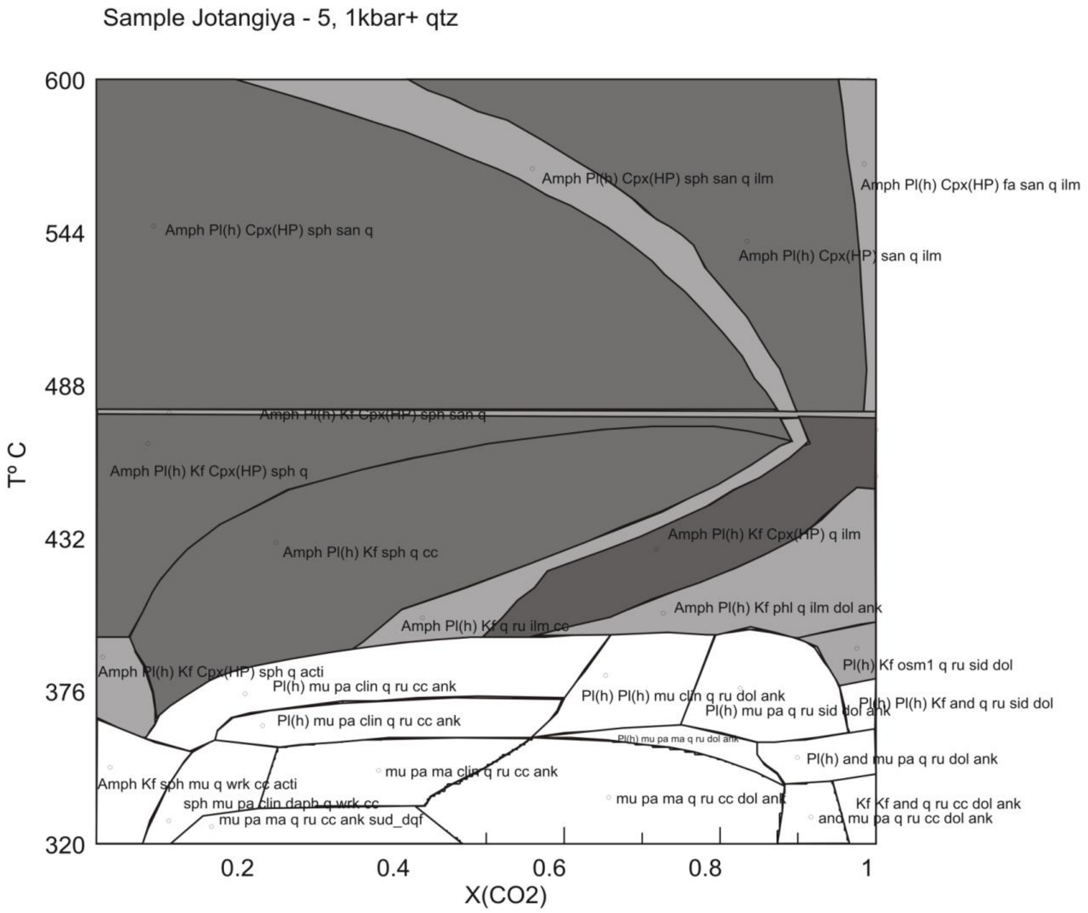
Phase Diagram Sections (Pseudosections):

Phase diagrams were computed as a function of calc-silicate whole-rock compositions via a free energy minimization strategy implemented in Perple_X version 6.8.1 (Connolly, 2005; Connolly, 2009). Thermodynamic data from the Holland and Powell dataset (1998) was employed for end-member calculations. Mixing properties of phases involving solid-solution were included in calculations. Pseudosections were modelled in the system: $K_2O\text{-}Na_2O\text{-}CaO\text{-}MgO\text{-}FeO\text{-}TiO_2\text{-}Al_2O_3\text{-}SiO_2\text{-}H_2O\text{-}CO_2$ (KNCFMASTCH) .Saturation of quartz (SiO_2) was assumed in calculations for quartz-bearing samples with bulk SiO_2 greater than 50 weight percent. Phase equilibrium calculations involving binary $H_2O\text{-}CO_2$ fluids were performed using the CORK equation of state from Holland & Powell (1991).T-X(CO_2) diagrams portray mineral equilibria and devolatilization reactions as a function of temperature and fluid composition.

All pseudosections were calculated for a temperature range of 300-600°C, fluid compositions between 0 and 1 for X(CO2) and at 1 Kbar of pressure. As according to (Butcher and Grapes 2011,) constant pressure of 1 kbar is considered for shallow level contact aureole and as mentioned earlier, these rocks offer the evidences of contact metamorphic effect. Here, an example of a sample GCSL-5 (Loc. JOTANGIYA) has been given.

The equilibrium assemblage Act + Cal + Qtz +Ttn ± Mc ± Pl ± Bt which was observed in thin-section of GCSL-5(Loc. JOTANGIYA) sample, used in calculations and derived the stability field with temperature range of 390°-600°C and wide range of fluid compositions of X(CO2) i.e. 0.1-1 (Fig.5). The destabilization of calcic amphibole (actinolite) above 390° C and occurrence of Cpx (diopside) defines the maximum temperature (~600C) predicted for this assemblage. Calcic amphibole occurs at most of the specified conditions excluding low temperatures (below 360°C) and high X(CO2) i.e. above 0.05) where it disappears with the appearance of low-temperature phlogopite at 400°C.

Carbonate-bearing fields occur over wide range of temperature i.e. ~327-427° C and fluid compositions of X(CO2) > 0.1 with calcite, ankerite, dolomite and siderite representing a part of protolith composition.. Phlogopite is stable as part of K-feldspar bearing assemblages at temperatures 400°C and at narrow range of fluid compositions. i.e.0.80-090. Potassium-feldspar is predicted in nearly all stability fields, from temperature 360-600°C and almost at all fluid compositions. Quartz is stable in the whole T-X(CO2) range of interest. Titanite is stable at temperature 360-600 ° C and at higher X(CO2) conditions but < 0.90.



(Fig.5)

Thermobarometry as well as Isobaric T-X(CO2) phase diagrams/pseudosections indicate that these rocks belong to the 'Hornblende–hornfels facies' of contact metamorphism.

To perform the comparative petrological studies of calc-silicate rocks from various areas of Southern Aravalli Mountain Belt (SAMB).

Comparative studies of calc-silicate rocks from Southern Aravalli Mountain Belt (SAMB) were carried out with respect to their petrography, mineral chemistry and bulk rock geochemistry. Apart from Lunavada Group, calc-silicate rocks of SAMB occur mainly in and around Champaner Group. Field studies were carried out in and around villages,viz. Wadek,Chalvad, Vav, Gandhra,Poyeli, Ambapani, Goldungari and Nanikhatva of Champaner region.

Earlier, stratigraphical (Gupta and Mukherjee,1938) and structural aspects (Joshi et al.2019) of Champaner Group were worked out in detail by previous workers, i.e. until the study related to the petrogenesis of calc-silicates in terms of petrography, mineral chemistry and geochemistry was undertaken.

The Champaner Group is considered to be the youngest group in the Aravalli Supergroup. It has been divided into six formations (Gupta et al., 1992) and the 'calc-silicate marbles' represent the second oldest formation i.e. 'Khandia Formation' (Srikarni and Das, 1996). The Champaner Group is also intruded by syn-post Godhra granite. The Champaner Group consists of meta-sedimentary rocks which include cyclic sequence of phyllite, quartzite and meta-conglomerate intercalated with minor-to-major bands of dolomitic limestone. The Champaner Group had experienced three episodes of deformation, viz. D_1, D_2 and D_3, which has developed F_1, F_2 and F_3 folds respectively. The first two phases of deformation are coaxial, to develop F_1 ~ ESE-WNW and F_2 ~ E-W trending folds. The third episode of deformation exhibits fold trends ranging from NNW-SSE to NNE-SSW (Joshi, 2018).

Field studies revealed the presence of unoriented amphibole needles as well as elephant skin weathering as characteristic features seen over these calc-silicates from Champaner area.

Petrography and Mineral chemistry of calc-silicates of Champaner Group:

The calc-silicates of Champaner group can suitably be termed as 'calc-silicate marbles' because unlike calc-silicates of Lunavada group ,these rocks have abundant presence of calcitic matrix (approx.70 %) and less number of calc-silicate minerals like calcic-amphibole, clinopyroxene, sphene etc. within it.

These rocks are characterized by the prominent hornfelsic texture. The typical assemblage of these calc-silicates is, calcite + tremolite + diopside + titanite +quartz + scapolite+ talc ± garnet ± chlorite ± plagioclase feldspar along with minor proportion of apatite and opaques.

By mineral chemistry studies of these rocks it can be understood that the calcic-amphibole as well as clinopyroxene presents within them are essentially tremolite and diopside respectively.

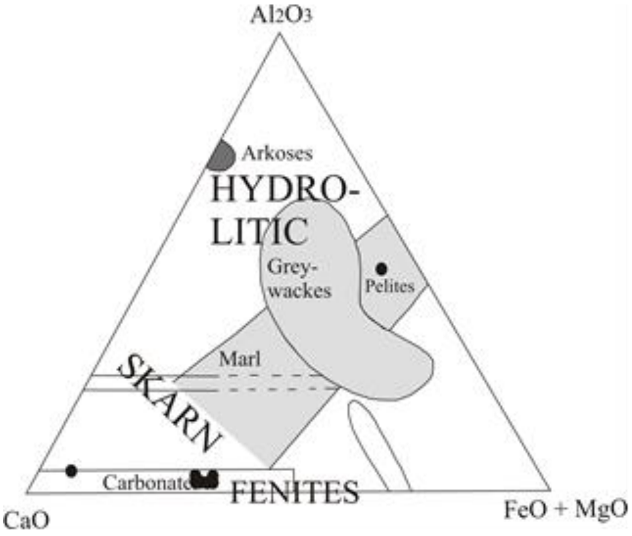
Whole rock geochemistry of Calc-silicates of Champaner Group:

Eight representative samples of the calc-silicate rocks of study area were analysed for determining major oxide, trace as well as rare earth elements (REEs) concentration.

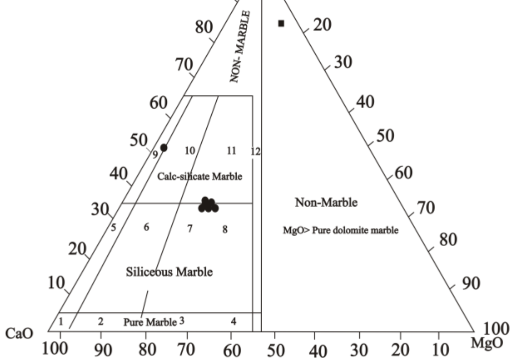
Major and trace element composition:

Analysed calc-silicate rocks exhibit a range of SiO_2 (15.7-36.9 wt.%), Al_2O_3 (0.5-3.6 wt.%) FeO (0.6-2.6 wt.%) and MnO (0.03-0.19 wt.%) which is lower than the average composition of post-archean upper continental crust (PAUCC) of Taylor and Mclennan (1985) whereas MgO (2.1-13.2 wt.%) and CaO (22.1-33.9 wt.%) whole-rock compositions show enrichment relative to the compositions of PAUCC.Analysed calc-silicates show concentrations of Zn(81-197 ppm), Ga(0.9-18.7 ppm) and large-ion-lithophile elements (LILEs) viz. Rb(2.3-261.1 ppm), Ba(18-1793 ppm), Sr (45.4-766.3 ppm), Pb (4.7-22.3 ppm), U(0.3-2.0 ppm) and Th (0.9-19.8 ppm) and high field strength elements (HFSEs) viz. Zr (19.1-257.7 ppm) and other elements like Cr (31-150 ppm),Ni (41.1-114.8 ppm),Cu (37.8-104.9 ppm) ,Co (2.6-13.8 ppm) have concentrations similar to PAUCC.

Following figure i.e (Fig.6) shows that the Calc-silicate bulk-rock compositions normalized to CaO, Al_2O_3, and FeO + MgO correspond closely to the carbonates. SiO_2 and Zr are positively correlated in these rocks which is possible only due to accumulation of Zr with quartz in sand fraction during sedimentation and recycling(Taylor and McLennan 1985; McLennan 1989; McLennan et al. 1990),also these rocks have plagioclase feldspar which implies the presence of little amount of quartzo-felspathic material within protolith. Similarly, the positive correlation between Al_2O_3 with Na_2O, feebly with K_2O and with nearly all measured trace elements implies that these elements are primarily controlled by the K-bearing minerals i.e. clay minerals and micas ,indicating protolith containing little amount of clay also. In a CaO-MgO-SiO_2 ternary diagram classification system for marbles (Storey and Vos 1981),(Fig.7) , most of the studied samples fall within the transition zone,i.e. from siliceous to calc-silicate marble. These observations indicate that the protolith of calc-silicates from champaner area must be impure limestone i.e. limestone having quartzo-felspathic or clayey impurities.

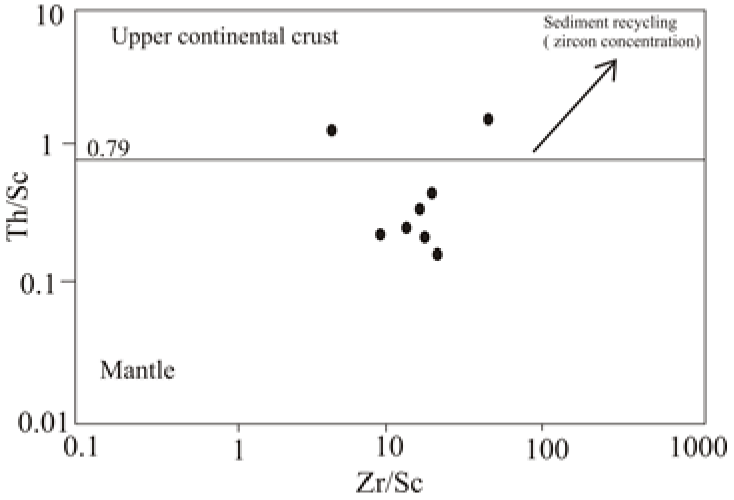


(**Fig.6.** CaO-Al_2O_3-FeO+MgO (wt. %) ternary diagram showing bulk rock compositions of Calc-silicate rocks of Champaner Group ,after Barton et al.1991).



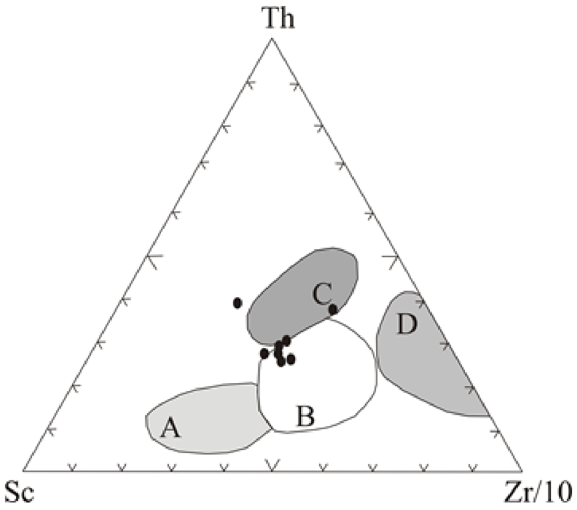
(**Fig. 7**. CaO-MgO-SiO_2 ternary diagram classification system for marbles ,after Storey and Vos 1981)

On Th/Sc-Zr/Sc plot (Fig.8) most of the samples fall in the mantle zone i.e below Th/Sc ratio having less than 0.79 value which indicates that a provenance was juvenile mafic. Similarly, detritus derived from a felsic source tend to be enriched in incompatible elements like Th, Zr and La, whereas those derived from a mafic source are enriched in compatible elements like Sc, Cr and Co (Ahmad et al. 2016). Here it has been observed that the calc-silicate rocks of the study area show enrichment in the incompatible elements viz. Sc, Cr and Co and are depleted in Th, Zr and La, thus emphasizing the mafic nature of provenance.



(**Fig.8.** Th/Sc vs Zr/Sc ratio diagram showing the composition of the sources for the primary sediments of calc-silicate rocks from Champaner area(after McLennan et al.1990).

On Sc- Th- Zr/10 plot of Bhatia and Crook (1986), sample data are plotted within the field ranging from continental island arc to active continental margin settings (Fig.9), indicating multiple sources /provenance for these calc-silicates (Naipauer et al.2010).



(**Fig. 9.** Sc- Th- Zr/10 ternary diagram of Bhatia and Crook (1986), plotting of calc-silicate samples from Champaner area)

Summary:

- Petrography and mineral chemistry of the calc-silicates of Lunavada helps to acquire some idea from observed assemblage, i.e. actinolite + diopside + quartz + titanite + calcite ± microcline ± biotite ± plagioclase feldspar ± epidote ± scapolite ± chlorite along with minor apatite, zircon and opaques as well as from accurate mineral compositions regarding protolith type. It is then confirmed with the help of whole rock geochemistry that the protolith is calcareous sandstone having various amount of quartzofelspathic and clayey material, as on CaO, Al_2O_3 and FeO + MgO ternary diagram, most of the calc-silicate samples fall within or very near to greywacke zone and also the positive correlation of Al_2O_3 with nearly all measured trace elements as well as with Na_2O and K_2O indicates protolith with clayey impurities.
- Th/Sc ratio (≥ 1) indicates evolved continental sediment sources which must be felsic, mostly granitic as indicated by enrichment of these calc-silicates in elements like Th, Zr and La as compared to Sc, Cr and Co. The protolith for these rocks must be deposited in active continental margin settings as is reflected from Sc-Th-Zr/10 ternary diagram. The temperature, about 600° C and pressure, about 0.88 Kbar estimated by conventional thermobarometry, is supported by isobaric T-X(CO2) diagram by which 'Hornblende-hornfels facies' of concluded metamorphism is concluded.
- When compared the petrological aspects of calc-silicate rocks of Lunavada Group

to those of the calc-silicates from Champaner Group some observations acquired related to petrography, mineral chemistry and geochemistry definitely distinguish these rocks from each other, i.e the calc-silicates from Champaner Group are having mineral assemblage, viz. calcite + tremolite + diopside + titanite +quartz + scapolite+ talc ± garnet ± chlorite ± plagioclase feldspar along with minor proportion of apatite and opaques which is different from the calc-silicate rocks of Lunavada Group with abundant calcitic matrix and less number of calc-silicate minerals thus categorizing them as ‘calc-silicate marbles’.

Similarly, as per mineral chemistry, the Ca-amphibole and clinopyroxene present within the rocks of Champaner are essentially tremolite and diopside, respectively. Geochemical studies revealed the protolith of calc-silicates of Champaner area as limestone having little amount of quartzo-felspathic as well as clayey impurities. Sediment source for these rocks found out to be mantle source i.e. juvenile and mafic conditions of provenance. The tectonic setting in which these rocks are occurring varies from continental arc to active continental margin indicating multiple sources.

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