Synopsis of the Ph.D. thesis entitled

Structural Evolution of Precambrian Rocks of Champaner Group, Gujarat, Western India

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Introduction:

Precambrian rocks of the north-western India viz. parts of southern Rajasthan and north-eastern Gujarat mainly comprises three important Proterozoic sequences, differentiated on the basis of depositional environment and tectono-magmatic events. These sequences encompass 1. The Bhilwara having an age more than 2500 Ma. 2. The Aravalli within time frame of 2500-2000 Ma. 3. The Delhi which ranges up to the time frame of 700 Ma. The meta-sediments and associated intrusive as well as extrusive igneous phases corresponding to these three Proterozoic sequences have been designated as the Bhilwara, the Aravalli and the Delhi Supergroups. These three Supergroups are further bifurcated to several Groups and Formations (Gupta et al., 1980; 1995; 1997).

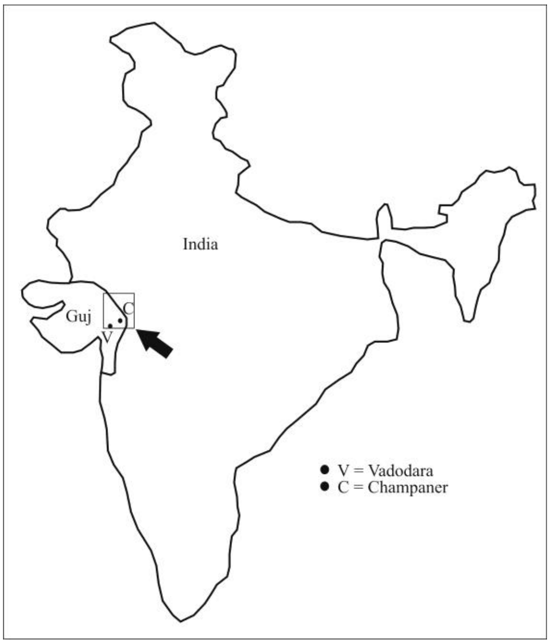

Fig.1: Location Map of the Study area

The Champaner Group of western India (Fig.1) is a part of Aravalli sequence exposed in Gujarat. Stratigraphically, the Champaner Group is considered to be the youngest group in the Aravalli Supergroup. It has been divided into six Formations separated on the basis of hetrogenity in terms of rock-type, strike persistency and occurrence of intraformational conglomerate (Gupta et al., 1992). The Champaner Group is also affected by syn-post Godhra granitic emplacement having range of dates from 1168-938 Ma (Joshi and Limaye, Inpress). The outcrops of the Godhra granite are exposed along the three marginal boundaries of the Champaner Group viz. northern, eastern and southern, whereas the western margin is obscured by the cover of thick Daccan trap and infratrapean rocks (Gupta et al., 1997). The Champaner Group consists meta-sedimentary rocks which includes cyclic sequence of phyllite, quartzite and meta-conglomerate intercalated with minor-to-major bands of dolomitic limestone. The regional metamorphic sequence possesses mineral assemblages like chlorite, muscovite and biotite that are consistent with the greenschist facies condition. On account of post thermal event these rocks show overprinting of contact metamorphic minerals like andalusite, cordierite, actinolite, tremolite and garnet, hinting towards hornblende-hornfels facies condition (Jambusaria and Merh, 1967; Jambusaria, 1970; Das et. al., 2009).

Structurally, the Champaner Group depict simple deformation pattern as compared to the older Groups of the Aravallis and younger Delhi Supergroup. The rocks belonging to the Champaner sequence have undergone two phases of deformation viz. D_1 and D_2. D_1 deformation persistent throughout the group which led to the development of open to tight isoclinal folds with axial traces trending in a WNW-ESE to E-W direction. D_2 phase of deformation is associated with folding of the earlier folds along the eastern margin to exhibit broad open folds with N-S striking axial traces on limbs of D_1 folds (Joshi et. al., 2014; Patel et. al., 2016; Jambusaria and Merh, 1967; Gopinath et al., 1977; Srikarni and Das, 1996; Gupta et al., 1997; Karanth & Das, 2000; Mamtani and Greiling, 2005). The fold morphologies thus illustrated are also characterised by axial planar slippages in the form of sinistral and dextral strike-slip faults, suggesting its post-folding chronology.

In early 1900's the Champaner Group grabbed a considerable heed due to the presence of manganese mineralization. Then after, majority of the work was carried out to refine its stratigraphic status with respect to the Dharwar rocks of South India, the Aravalli rocks of Rajasthan and the Delhi rocks of north-eastern Gujarat (Blanford, 1869; Fermor, 1909; Heron 1917; Rama Rao 1931; Gupta and Mukherjee, 1938). Jambusaria (1970) gave a detail outline of rocks belonging to Shivrajpur and surrounding regions in terms of stratigraphy, structure and metamorphism. In his work he immensely advocated that the Godhra granitic intrusion has greatly amended the pre-existing structures of the Shivrajpur and the surrounding region. However, he didn't explain the structural disposition of the Champaner Group as a whole with respect to the neighbouring Precambrian Stratigraphic units. In the light of hitherto work, more research is needed to address the surface and the sub-surface structural complexity pertaining to the Champaner Group in terms of its evolution as well as to determine the role of the Godhra granitic emplacement in response to the existing deformation. In order to fulfill the said research gap following objectives were defined.

Research Objectives:

1. To unravel the deformational history of the Pre-Cambrian rocks of the Champaner Group.
2. To appreciate the micro scale derivatives of deformation due to change in temperature and pressure conditions.
3. To establish the time relationship between deformation and metamorphism of meta-sedimentary rocks of the Champaner Group.
4. To address the surface and sub-surface structural complexity of the Champaner Group.
5. To understand the role of Godhra granite in defining the structural framework of the Champaner Group.

Methodology:

1. Detail field work was carried out in order to record the planar and linear structural elements present within the study area.
2. Anisotropy of Magnetic Susceptibility (AMS) of mono-mineralic and/or non-foliated rocks was carried out to understand the orientation of the magnetic foliation.
3. Microstructural analysis from the thin-sections was carried out to understand micro-scale deformation and to establish time relationship between deformation and metamorphic crystallization.
4. Electron Micro-Probe analysis of selective opaque prophyroblasts in meta-pelites was carried out to understand the mineral composition.
5. Cost effective Microtermor technique was applied in order to decode the depth, sub-surface extension and the structural complexity of the mn-bearing meta-sedimentary rocks of the Champaner Group.

Results and Discussions:

The results obtained by applying the above methodologies are synthesized to achieve the proposed objectives:

To unravel the deformational history of the Pre-Cambrian rocks of the Champaner Group:

The information obtained from the topographic sheet No. 46 F/10, 11, 14 and 15 of 1:50,000 scale have been used to select decisive areas for detail mapping. With the help of topographic sheet appropriate traverses have been outlined. On these traverses the planar and linear structural elements have been acquired from different field season and carefully plotted over the base map to prepare the structural map of the study area. More emphasis has been given to the plunge amount, plunge direction, pitch amount and measured direction of pitch, in case of linear structural element; where as for planar structural element strike, dip direction and dip amount were measured. The prepared geological map was then divided into sub-areas, depending on the dominancy of the fold events. This has been supplemented with the help of Schimdt Equal Area Stereographic projection. The present study has provided an insight to unravel the complexities in terms of surface structures of the area. The result signifies that there is more than one set of folds, which are found to be coaxially folded along similar trend. Another set of folds are orthogonal to the earlier axial traces. The analyses have led to understand different fold interference pattern present within the study area.

One of such location situated at Narukot within the Khandia and Narukot Formation has been worked out in detail, which provides significant insight in terms of overall deformation undergone by the Champaner Group of rocks.

Regional-scale fold mapping carried out at the “Narukot dome” differs from the existing structural set up presented by the earlier workers. Domal appearance at Narukot is composed by the combination of F_1 to F_3 folds regionally. In order to carry out the structural analysis the area has been divided into sub-areas, representing F_1, F_2 and F_3 dominated regions respectively. One of the sub-area represent F_1 fold with an axial trace dipping due WNW in Khandia schist located at the eastern part of the dome. F_1 fold has resulted due folding of S_0 bedding plane by generating S_1 schistosity plane. Due to the manifestation of F_2 over F_1, S_0 show sub-parallel relationship with S_1 and axial planar S_2 schistosity plane has been developed generating L_2 lineations on S_0. These lineations are intersection lineations formed by S_2-S_0 intersection, which plunges 46^o in the direction of N279^o and form pucker axis over the hinge line. By plotting several such lineations over lower hemisphere stereographic projection, the orientation of π_1 axis fits well with the pucker axes lineations obtained from the field. The fold is moderately inclined having pitch of the F_1 fold axis 47^o in the direction of N 280^o (WNW) measured on S_0 plane. Tight to isoclinal F_2 folds affected quartzite band as F_1 folds refolded along similar trend. In quartzites the S_0-S_1 relationship is sub-parallel to each other and S_0 dips slightly steeper as compared to S_1. S_2 orientation is feeble and mostly appears as discrete cleavages to form L_2 intersection lineations between secondary cleavage planes and S_0 over S_1. π_2 axis of F_2 fold matches with the data set of intersection lineations recorded from F_2 dominated area. The core of the F_2 fold is traceable for 1 km at the western margin of the Narukot dome. The N and the S limb of F_2 strike ~ E-W having due N and due S dip directions, respectively. The fold axis plunges towards W with an amount of 20^o and possess a sub-vertical axial plane. Another sub-area depicts F_3 open fold trending N-S axial trace over km long limbs of F_1 and F_2 fold. The axial plane can be traced from the N to the S fringe of the dome dividing it into two ~ equal portions. Steeply dipping mesoscopic F_3 fold axes has been observed along outer rim of quartzite near SW of Wadek. These lineations fit well with the fold axis π_3. The fold possess vertical axial plane and have a northerly plunge of its axis.

An attempt has been made to study the derivates of these three fold events across the Champaner Group. The results signifies that further to the W of the Narukot dome, where the younger Formation of the Champaner Group are encountered, F_1 fold exhibit second order tight and F_2 folds as first order open with varying amplitude versus wavelength ratio. The ratio for F_1 folds has been calculated in the field as the folds are meso-scopic in nature. The ratio ranges from 2:1 to 3:1, obtained along 3-4 mt length across 3-6 sq mt area. However, for F_2 folds the ratio ranges from 1:4 to 1:5, obtained along 1-2.5 km length across 0.5-1.5 sq km area. These F_2 folds ratios has been acquired through satellite image and validated during mapping. F_3 fold gradually die out in the form of maga-scale open wraps to meso-scale kink bands from eastern to the western stretch of the Champaner Group, respectively.

Analyses of individual folds from F_1 to F_3 at Narukot were helpful in interpreting the regional-scale deformation interference pattern. The combination of F_1 and F_2 fold has generated map scale hook or Type-III interference pattern of (Ramsay 1962; Ramsay and Huber, 1987), demonstrating a comprehensive hammer head anticlinal structure. Their fold axes are sub-parallel (F_1~WNW; F_2~W) with ~ orthogonal axial planes. Overprinting of F_3 fold on F_1 and F_2 developed regional-scale dome and basin geometry or Type-I interference pattern (Ramsay 1962; Ramsay and Huber, 1987). Moreover, N-S trending F_3 fold developed by E-W shortening has its maximum effect along the eastern margin of the Champaner Group by closing up of domes at Narukot and Poyli areas.

Another example from out-of-sequence deformation has been worked out at Jothwad region east of the Narukot dome (Joshi and Limaye, Inpress). At Jothwad region isolated calc-silicate bands from khandia Formation records signatures of out-of-sequence deformation due to post-tectonic granite. The Jothwad region, a part of the Champaner Group represent superimposition of Type-II interference pattern over cylindrical upright fold. Moreover, this interference fold patterns is rootless and depict no continuity in the subsurface as well as are unmatched with the existing structural set up of the Champaner Group.

To appreciate the micro scale derivatives of deformation due to change in temperature and pressure conditions:

The study of this section explains all micro scale derivatives formed on account of deformation due to change in temperature and pressure conditions. The section has been divided into a. Shear Induced Microstructures (SIMs) and b. Temperature Induced Microstructures (TIMs) and c. Complex Microstructures (CMs)

a. SIMs:

The SIMs displays derivates of shears with the help of opaque porphyroblasts in phyllite-mylonites of the study area. Mylonites are the product of ductile deformation and display significantly recrystallization of the matrix. The role of shear sense indicators within mylonites becomes vital in order to define direction of movement i.e. sinistral or dextral, normal or reverse or sense of shear. These shear sense indicators includes (i) displacement of markers (ii) foliation curvature (iii) shear band cleavage including C/S fabrics (iv) mantled porphyroclasts (v) mineral fish (vi) quarter structures (vii) lattice preferred orientation. The porphyroclasts which serve as a reference for displacement are commonly consisting of feldspar, garnet, micas, hornblende and pyroxenes. The presently known examples forming mineral fishes are biotite, tourmaline, K-feldspar, garnet, plagioclase, staurolite, kyanite, amphibole, hypersthene, diopside, apatite, rutile, hematite, prehnite, Leucoxene, sillimanite, olivine and quartz (Passchier and Trouw, 1996). Porphyroclast systems and variety of fishes of opaque in phyllite-mylonite have been identified. The mantled porphyroclast systems include σ and δ of stair stepping variety and φ type porphyroclasts with strain shadows. All variety of fishes of opaque from Group 1- 6 have been recognised which gives reliable sense of shear. Other important microscopic shear sense indicators include quarter structures and pinch and swell microstructures. Microscopic shear sense indicators in phyllite-mylonite consistently show top-to-east sense of ductile shearing.

b. TIMs:

The TIMs mainly show derivatives from monomineralic rock (i.e.) quarzties belonging to the Champaner Group. Total 46 samples of quartzite through grab sampling method were collected, which are ubiquitous in each formation. TIMs identified from quartzites are Bulging Recrystalization (BLG); Sub-grain Rotation Recrystallisation (SGR); Grain Boundary Migration Recrystallisation (GBM) and Grain Boundary Area Reduction (GBAR). The microstructures mentioned above in the quartzites were used to understand the micro-scale deformation mechanism and thermal characterization of the Godhra granite. Heat imparted by granite and related stresses are reflected in microstructures due to variation in its proximity to granitic intrusion. For instance, western part of the Champaner Group show BLG; SGR and GBM microstructure with the presence of clear extinction, whereas the eastern part exhibit GBAR as a dominant microstructure due to intense heat along with undulose extinction.

c. CMs:

Oppositely Concave Microfolds Microstructures (OCMs) inside andalusite host has been categorized under Complex Microstructures (CMs). The andalusite mineral possesses quartz inclusions in the form of microfolds. These microfolds are formed in an oppositely concave fashion and are interpreted as relict ductile shear evidences within the contact aureole associated to the Narukot Formation of the Champaner Group. Microstructural investigations suggest that the trails of OCMs in andalusite are discontinuous outside the porphyroblast and exhibit top-to-left sense of ductile shear. The hindrance of internal-to-external fabric from the porphyroblast to the ground mass is on account of muscovitisation by metasomatic fluids and recrystallization process due to late thermal event.

To establish the time relationship between deformation and metamorphism of meta-sedimentary rocks of the Champaner Group:

The phyllites and calc-silicates of the Champaner Group are used to understand the time relationship between deformation and metamorphism. The Zwart (1962) scheme has been applied to identify the porphyroblasts-matrix relations. Mineral fabric developed on account of regional metamorphism forms the matrix or Se (external schistosity plane), whereas the porphyroblasts possessing quartz inclusions are considered as Si (internal schistosity plane). Based on Si and Se relationship the growth of the porphyroblasts is differentiated either as Pre; Syn; Inter or Post in nature. In case of inter-tectonic porphyroblasts the four fold classification proposed by Passchier and Trouw (1996) has been adopted. In addition to that the extinction posses by the inclusions of quartz inside the porphyroblasts are taken into consideration to explain the effect of the post intrusive granite present in vicinity of the study area. For example the minerals in the meta-pelites and calc-silicates of the study area developed on account regional metamorphism forms the external fabric. These minerals include chlorite, muscovite, biotite, calcite and quartz, whereas mineral such as cordierite, andalusite, granet, actinolite and tremolite show quartz inclusions as internal fabric. In all three metamorphic events have been identified (i.e.) M_1, M_2 and M_3 which are coeval with the three deformational events viz. D_1, D_2 and D_3. The latest metamorphic event M_3 has been further classified as M_{3a} and M_{3b}. M_{3a} has developed on account of D_3 deformation, where as M_{3b} signifies contact metamorphism, which is devoid of any deformation. However, any effect of retrogressive metamorphism has not been observed in the study of these meta-pelitic and calc-silicate rocks.

To address the surface and sub-surface structural complexity of the Champaner Group:

In order to address the surface structural complexity pertaining to the rocks of the Champaner Group, detail structural mapping of the decisive areas have been carried out. Moreover, an array along the axial trace of the folds covering entire Formations of the Champaner Group has been worked out in detail. The surface structural trends of mesoscopic fold axes along with all possible readings of beddings and foliations have been acquired. Sub-surface mapping of this specific array has been carried out using cost effective Microtremor technique (Joshi et al., 2018). Total 32 sites have been selected along 22 km long profile line. Fourier amplitude spectral studies were applied to obtain the ratio between the horizontal and vertical components of persisting Rayleigh waves as local ambient noise. Fundamental resonant frequencies with amplitude ≥1-sigma for each site are considered to distinguish rheological boundary. Two distinct rheological boundaries are identified based on frequency ranges determined in the terrain: (1) 0.2219–10.364 Hz recorded at 31 stations identified as the Champaner metasediment and granite boundary, and (2) 10.902–27.1119 Hz recorded at 22 stations identified as the phyllite and quartzite boundary. The morphology of granite pluton represents the rootless character of Champaner Group. The findings suggest that pluton at a shallower depth imply a steep easterly plunge within the Champaner metasediments, whereas signature of pluton at a deeper level implies a gentle westerly plunge. The present method enables to assess how granite emplacement influences the surface structure.

To understand the role of Godhra granite in defining the structural framework of the Champaner Group:

Granites located in and around the Champaner Group of rocks display signatures of syn to post plutonic emplacement (Joshi and Limaye, Inpress). Distinguishing characteristic of syn/ post-tectonic granite can be very well appreciated along the east of the Jhand area, where coarse-grained post-tectonic granite is having intrusive relationship with the fine-grained syn-tectonic granite (Joshi and Limaye, 2014). The coeval pulse of granite emplaced during progressive deformation has magnetic foliation trending WNW to WSW. Feldspar laths within syn-tectonic granites too trend WNW to W striking trends (Mamtani 1998; Mamtani *et al.*, 2002; Mamtani and Greiling, 2005; Sen and Mamtani, 2006). Existing geochemical records of syn-tectonic granite suggest that the granite is of 'S-type' evolved on account of partial melting of the continental crust during continent-continent collision (C-C) (Merh 1995; Goyal *et al.*, 1997).

The granite of post-tectonic nature is characterised by forceful emplacement deforming the country rocks along N-S trend and developed strike slip faults of sinistral/ dextral nature along pre-existing axial planar weak zones throughout the group. The model given by (He et al., 2009) for Fangshan pluton, SW Beijing, forms the rim syncline along the margin of the pluton. Similar style of N-S trending rim synclines are found to be developed along the eastern margin of the Champaner Group bordering the pluton. The post tectonic granite having the geochemical affinity of 'A-type' representing transitional or post-orogenic uplift (suggested by Maithani *et al.*, 1998; Goyal *et al.*, 2001), has been intruded by accommodating the space within the Champaner metasediments and pre-existing syn-tectonic pulse. Such inference has been derived by collecting xenolith evidences of (i) Champaner meta-sediment and (ii) fine grained granite from coarse grained granite variety. One such location is at the north-eastern fringe of the Champaner region near Sukhi dam, where intrusive contact between Godhra granite and Champaner meta-sediments is exposed.

Summary:

- The present study explains deformational history pertaining to the rocks of the Champaner Group through detailed structural mapping. The investigation reveals that there are three deformational phases recorded within the Champaner meta-sediments. First two folds were coaxial and were on account of N-S to NNE-SSW compression that resulted in E-W to WNW-ESE striking axial planes. These two events resulted in development of Type-III interference pattern. Subsequently, the rocks were superimposed by a third deformation. This was due to E-W compression that resulted in development of N-S striking axial planes. The superposition of third folding over earlier two folds led to dome-basin (Type-I) interference pattern.
- Time relationship between deformation and metamorphism has been established which indicate that there are three metamorphic events (i.e.) M_1, M_2 and M_3 which are coeval with the three deformational events viz. D_1, D_2 and D_3. The latest metamorphic event M_3 has been further classified as M_{3a} and M_{3b}. M_{3a} has developed on account of D_3 deformation, where as M_{3b} signifies contact metamorphism, which is devoid of any deformation.
- Microstructural investigations suggest that there are three varieties of microstructures present within the study area. These microstructures can be differentiated as Shear Induced Microstructures (SIMs) and Temperature Induced Microstructures (TIMs). The mantled porphyroclasts systems and Group 1-6 opaque fishes are categorized under SIMs, whereas BLG, SGR, GBM and GBAR represent TIMs varieties.
- Geophysical investigation through Microtremor method suggest that there exists subsurface pluton below the Champaner meta-sediments, which implies to the rootless character of the Champaner Group. The present method enables to assess how granite emplacement influences the surface structure.
- Granites located in and around the Champaner Group of rocks display signatures of syn to post plutonic emplacement. The coeval pulse of granite emplaced during progressive deformation has similar magnetic foliation to that of Champaner meta-sediments. The syn-tectonic granite is of ‘S-type’ evolved on account of partial melting of the continental crust during continent-continent collision (C-C). The granite of post-tectonic nature is characterised by forceful emplacement deforming the country rocks along N-S trend and developed strike slip faults of sinistral/ dextral nature along pre-

existing axial planar weak zones throughout the group. The post tectonic granite having the geochemical affinity of ‘A-type’ representing transitional or post-orogenic uplift.

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