Rootless calc-silicate folds in granite: An implication towards syn- to post-plutonic emplacement

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Deformation of the Champaner Group of rocks that form a part of Southern Aravalli Mountain Belt, western India, occurred during the Grenville orogeny (ca. 1400–935 Ma). Two phases of deformation are recorded: D₁, persistent throughout the group and characterised by westerly plunging tight isoclinal folds and D₂, a localized phase of deformation associated with shortening of the earlier folds from the eastern margin. Both the phases of deformation are in association with the syn-tectonically emplaced Godhra granite. The present work records rootless calc-silicate folds in granite belonging to the older formation, located at the eastern fringe of the Champaner Group. Field evidences suggest superimposition of Type 2 interference pattern trending NE–SW over rootless Type 0 of varying trends from NW–SE to N–S. The superposed pattern obtained from the field study differs in terms of structural trends with the neighbouring Precambrian stratigraphic units. These stratigraphic units include the Champaner Group to which the study area belongs, the Kadana Formation of the Lunavada Group and Pre-Champaner Gneissic Complex. Rootless character of folds found within the study area imply syn-post plutonic emplacement of Godhra granite.

Keywords. Grenville orogeny; Champaner Group; Southern Aravalli Mountain Belt; deformation; rootless folds; Godhra granite.

1. Introduction

The Champaner Group forms the youngest group in the Aravalli Supergroup, located at the eastern fringe of Gujarat and it occupies entirely the Shivrajpur, Jambughoda and Bodeli region (Gupta *et al.* 1992, 1995, 1997). The Champaner Group forms the part of southernmost extension of the Southern Aravalli Mountain Belt (SAMB) in Gujarat and is located at the junction between the two older sequences, viz., the Lunavada Group in the north and pre-Champaner rocks in the

southeast direction. Rocks of the SAMB displays significant variation of the structural trend from NE–SW to E–W in Gujarat and continues to exhibit NW–SE trend in the older Pre-Champaner rocks extending right up to parts of Jhabua district of Madhya Pradesh (figure 1a).

The Champaner Group is intruded by younger plutonic rocks, i.e., Godhra granite to the northern, eastern and the southern margins, whereas obliterated by the cover of thick Deccan volcanic rocks and recent sediments along the western margin (figure 1b). Numerous available dates on age of

Figure 1(a). Lithostratigraphic map of Southern Aravalli Mountain Belt, NW, India (modified after Mamtani and Greiling 2005).

Godhra granite have a time range of 1168–938 Ma suggesting prolonged emplacement period (Rb/Sr method 1168 ± 30 Ma: Srimal and Das 1998; Sm–Nd method 1050 ± 50 Ma: Shivkumar *et al.* 1993; Rb–Sr method 965 ± 40 Ma: Goyal *et al.* 2001; Rb–Sr method 955 ± 20 Ma Gopalan *et al.* 1979; Rb–Sr method 950 Ma, Crawford 1975; Rb–Sr method: 938.8 ± 20 Ma: Srimal and Das 1998). Lithologically, the Champaner Group consists of a sequence of meta-subgreywacke, sandy phyllite, graphite-schist, quartzite, polymictic meta-conglomerate, dolomitic limestone and manganese phyllite (Gupta *et al.* 1980, 1997). The grade of regional metamorphism has reached up to greenschist facies condition, which is implied

by the development of chlorite, muscovite and biotite, whereas hornblende hornfels facies characterise the contact metamorphic condition giving rise to the development of pelitic hornfels and skarns (Jambusaria and Merh 1967; Das *et al.* 2009).

Structurally, the entire sequence depict simple deformation pattern as compared to the Aravalli and Delhi Supergroup. The rocks of the Champaner Group have undergone two phases of deformation, viz., D₁ and D₂. D₁ deformation dominates 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. D₂, a localized phase of deformation associated with shortening of the earlier folds from the eastern margin of the Champaner Group signifying broad open folds with N–S striking axial traces developed on regional limbs of D₁ folds (Jambusaria and Merh 1967; Gopinath *et al.* 1977; Srikarni and Das 1996; Gupta *et al.* 1997; Karanth and Das 2000; Mamtani and Greiling 2005; Joshi and Limaye 2014; Patel *et al.* 2016). There also exist signatures of D₁ axial planar strike slip faults and shear zones across the Champaner Group (Joshi *et al.* 2018). Due to the heterogeneity in terms of manganese beds and structure, a suggestion has been made that the Champaner Group be described as a sequence younger to both Aravalli and Delhi Supergroup (Roy 1988).

The paper focuses on field evidences of isolated and deformed calc-silicate band of Khandia Formation of the Champaner Group, occur as enclaves within younger granite. The present study will be helpful to understand the effects of prolonged emplacement period of Godhra granite in the region and will be helpful to resolve the stratigraphic debate pertaining to the structure of the Champaner Group of rocks. The study area is in-and-around Jothwad village, located at the eastern fringe of the Champaner Group. Detailed structural mapping has been carried out in the terrain. Structural attributes acquired from the field work have been plotted on stereographic projection to interpret the fold pattern. The inferences derived from (i) the field evidences; (ii) the existing Anisotropy of Magnetic Susceptibility (AMS) data from Godhra granite, and (iii) the existing subsurface shallow seismic profiling using cost effective Microtremor technique are used to explain the syn-post plutonic emplacement with D₁ deformation of the Champaner Group of rocks.

Figure 1(b). Generalized geological map of the Champaner Group and neighbouring areas (modified after Jambusaria and Merh 1967 and Gupta *et al.* 1997). Filled red square indicates the study area.

2. Geological and structural set-up of the study area

The study area is the part of Khandia Formation of the Champaner Group, Aravalli Supergroup. The Khandia Formation is considered to be the second oldest formation of the Champaner Group (table 1), primarily composed of phyllite, quartzite, dolomitic limestone and metasubgreywackes (Gupta *et al.* 1997). However, the area under investigation consists of calc-silicate rock of Meso-Proterozoic age enveloped by younger plutonic intrusive, i.e., Jambughoda granite (Goyal *et al.* 1997). Jambughoda granite is the part of Godhra granite, emplaced along a major NW–SE Precambrian trend (Mamtani and Greiling 2005; Joshi *et al.* 2018).

As shown in the geological map of the Jothwad region, the deformed calc-silicate rock is at the

centre followed by a thin rim of granite having enclaves of calc-silicate rock, which further grades into massive, medium to coarse grained, leucocratic granite (figures 2, 3a). The calc-silicate rock is greenish grey in colour, fine to coarse grained and massive in nature. At places, the calc-silicate exhibit caught up folded fragments embedded in granite (figure 3b). The intrusive contact between calc-silicate rock and granite can be appreciated along the excavated pit located in vicinity of the study area. The side face of 5 m deep pit was studied in order to examine the subsurface extent of calc-silicate rock (figure 3c). Minerals that can be identified in the hand specimen include wollastonite, actinolite, piemontite and winchite, forming typical skarn rock mineralogy (Das *et al.* 2009).

Structurally, rocks of the study area are poly-deformed and exhibit two sets of fold, viz., F_1

Table 1. *Proterozoic stratigraphic succession of Gujarat and south Rajasthan (after Gupta et al. 1980, 1992).*

Proterozoic Stratigraphic succession of Gujarat and South Rajasthan		
P R O T E R O Z O I C	Malani Igneous Suite	Intrusives Post-Delhi
	Erinpura Granite	
	Godhra Granite and Gneiss	
	Punagarh Group	Delhi SuperGroup
	Sirohi Group	
	Sendra Ambaji Granite and Gneiss	
	Phulad Ophiolite Suite	
	Kumbhalgarh Group	
	Gogunda Group	
	Champaner Group - Rajgadh Formation Shivrajpur Formation Jaban Formation Narukot Formation Khandia Formation Lambia Formation	Aravalli SuperGroup
	Lunavada Group	
	Synorogenic Granite and Gneiss	
	Rakhabdev Ultramafic Suite	
	Jharol Group	
	Bari lake Group	
	Udaipur Group	
	Debari Group	
ARCHAEAN	Basement Complex	Bhilwara SuperGroup

and F_2 . The northwestern and the southern parts of the study area depict mesoscopic rootless tight/isoclinal F_1 folds (figure 3d, e). The axial plane in the northwestern part strike NW–SE and fold axes plunges in the direction of $N120^\circ$ with an amount of 50° , whereas in the southern part of the study area, trend of the axial plane is N–S and fold axes plunges due N with an amount of 52° . By plotting poles of S_1 foliation collected

from the entire study area, F_2 axial trace has been projected by using lower hemisphere stereographic projection (figure 3f). F_2 fold is broad open type synformal structure trending NE–SW and fold axes plunges in the direction of $N30^\circ$ with an amount of 62° . The superimposition of F_1 and F_2 folds has resulted in development of Type 2 interference pattern over Type 0 (i.e., non-plane non-cylindrical fold over plane cylindrical folds).

Figure 2. Geological map of the Jothwad region (study area).

The outcrop pattern due to Type 2 interference has resulted in mushroom shaped geometry (figure 3g).

3. Discussion and conclusion

Based on the field evidences of the Jothwad region (figure 3a–e), the folds are rootless and depict no continuity in the subsurface; moreover, they also occur as enclaves in the granite. Therefore, it is suggested that the folding in the study area was prior to the emplacement of the plutonic body. The existing structural set-up adjacent to the study area depict variation in the structural trend, i.e., the Champaner metasediments at the west are characterized by two phases of deformation $D_1 \sim$ E–W to ESE–WNW and $D_2 \sim$ N–S and the Pre-Champaner rocks located at the SE, which consists four phases of deformation from D_1 to D_4 . D_1 is characterized by rootless recline folds of N–S trend, where as D_2 and D_3 show E–W trend with varied fold morphologies. Finally, D_4 depict N–S trending warps and kinks. However, last two phases of deformation of Pre-Champaner rocks are pronounced over the Champaner metasediments (Karanth and Das 2000; Das 2003).

The existing structural set-up of the Jothwad region is not only in contrast with the adjacent

Champaner and Pre-Champaner rocks, but also differ from the regional structural set-up of the Southern Aravalli Mountain Belt (SAMB), which includes: (1) The Banded Gneisses at the northeast, (2) the Lunavada Group extended till south of Devgadhi Bariya in the north, (3) Pre-Champaner Gneisses at the southeast, (4) the detached Champaner metasedimentary sequence in the west, and (5) Godhra granite in which the study area is located (figure 1a).

Table 2 shows a summary of deformation events recorded in the neighbouring Precambrian stratigraphic units and its relation with the study area. The inferences derived from existing Anisotropy of Magnetic Susceptibility (AMS) data and preferred orientation of feldspar laths from Godhra granite suggest that the range of magnetic foliation in granite strike WNW to WSW and preferred orientation of feldspar laths within granite trends WNW to W (Mamtani and Greiling 2005; Mamtani *et al.* 2002; Sen and Mamtani 2006). The prevailing structural trends, which are correlatable with synchronous Godhra granitic emplacement are: (1) D_3 structures in the Banded Gneisses, (2) D_3 structures in the Lunavada Group of rocks, (3) D_2 and D_3 structures in the Pre-Champaner Gneisses with different fold morphology (a. Recline and b. Upright), and (4) D_1 structures in the Champaner Group of rocks. Though the AMS data from

Figure 3. (a) Enclaves of calc-silicate rock in granite (camera faces in eastern direction); (b) Caught up folded fragment of calc-silicate rock embedded in granite (camera faces in southeastern direction); (c) Dotted line demarcates inferred contact between weathered calc-silicate rock and granite at the side face of 5 m deep pit, in vicinity of the study area (camera faces in western direction); (d) Tight to isoclinal folds in calc-silicate rock in the NW part of the study area (camera faces in southeastern direction); (e) Tight to isoclinal folds in calc-silicate rock in the south part of the study area (camera faces in southern direction); (f) Lower hemisphere stereographic projection of the structural data related to F_2 folds, collected from the Jothwad region. Plotting of poles of S_1 foliation collected from the entire study area. Note that the F_2 fold axes (π_{II}) perpendicular to common great circle plunge towards the NE direction; (g) Mushroom-shaped outcrop geometry on account of Type 2 interference (camera faces in northeastern direction).

Godhra granite is found to be concomitant with neighbouring Precambrian stratigraphic units, it is unmatched with the trends recorded within the study area.

Wide range of dates on age of Godhra granite as mentioned in section (1) indicate longer time span of emplacement, i.e., from 1.1 to 0.93 Ga. However, the deformation date for the Champaner

Table 2. Summary of deformation events recorded in different Precambrian stratigraphic units and its relationship with the study area. Structural records from the Banded Gneisses and the Lunavada Group after [Mamtani \(1998\)](#) and [Mamtani et al. \(1999a, b, 2000\)](#); [Mamtani and Greiling \(2005\)](#), data from the Pre-Champaner Gneisses after [Karanth and Das \(2000\)](#); [Das \(2003\)](#), Godhra granite magnetic data and preferred orientation of feldspar laths after [Mamtani and Greiling \(2005\)](#); [Mamtani et al. \(2002\)](#); [Sen and Mamtani \(2006\)](#). Bolded columns in the row indicate correlatable axial trace trends with synchronous Godhra granitic emplacement.

The Banded Gneisses located at NE	The Lunavada Group extended till south of Devgadhi Bariya located at the N	The Pre-Champaner Gneisses located at the SE	The Champaner Group located at the W	The Jothwad region (study area) located within the Godhra granite boundary	Godhra Granite Surrounding the study area
D ₁ and D ₂ coaxial having axial trace trend NE–SW to ENE–WSW	D ₁ and D ₂ coaxial having axial trace trend NE–SW	D ₁ having axial trace trend N–S of recline folds	–	–	–
D₃ having axial trace trend ESE–WNW to ENE–WSW	D₃ having axial trace trend E–W to NW–SE	D₂ and D₃ having axial trace trend E–W with different fold morphology (a. Recline and b. Upright)	D₁ having axial trace trend E–W to ESE–WNW	D ₁ having axial trace trend NW–SE to N–S	Preferred orientation of feldspar laths trend ESE–WNW; magnetic foliation trend ESE–WNW to ENE–WSW
–	–	D ₄ having axial trace trend N–S upright warps and kinks	D ₂ having axial trace trend N–S	D ₂ having axial trace trend NE–SW	–

metasediment is still undetermined. Northern extremity of Godhra granite is marked by the contact with the Lunavada Group of rocks. The field evidence for granite and related pegmatites intruding foliation in schists of Kadana Formation, Lunavada Group, indicates that the intrusion continued even after D₃ deformation of the Lunavada region. Microstructural records specify advent of thermal event related to late D₃/post-D₃ Godhra granitic intrusion in the Lunavada terrain (Mamtani and Karanth 1996; Mamtani *et al.* 2001). Based on which, a possibility can be determined that D₃ deformation of the Lunavada region and D₁ deformation of the Champaner region were coeval events (Mamtani and Greiling 2005). The above inference also deflates the suggestion given by Roy (1988) to reorder the stratigraphic position of the Champaner Group over Delhi Supergroup.

Microtremor measurements carried out at 32 sites along D₁ axial trace of Narukot Dome and its western extension by Joshi *et al.* (2018) is helpful to identify two distinct rheological boundaries based on frequency ranges determined in the terrain. These rheological boundaries include (i) the juxtaposed Champaner metasediment over granite (C–Gr) boundary and (ii) intercalated phyllite and quartzite (P–Qr) boundary. Out of which, (i) C–Gr boundary lies in vicinity of the study area at station 31. The inferences derived by the subsurface shallow seismic profiling using microtremor technique indicate that the sporadic granitic plutons emplaced in the terrain have uprooted the Champaner metasediments giving ‘rootless’ characteristic in the study area and at the Narukot dome as well as to its western extension.

All above evidences lead to the conclusion that even after the D₁ deformation of the Champaner Group of rocks, the Godhra granitic emplacement continued to give rise rootless folds along with caught up fragments in the granitic mass of the Jothwad region. This prolonged emplacement also probably uprooted the Champaner metasediments exposed in the western part of the study area.

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