**Brief Resume of Mr. Aditya Udayraj Joshi**
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**List of Research Articles (Published/ Accepted) from Ph.D. Thesis:**

- **Aditya U. Joshi (Inpress)** Fold Interference patterns in Meso-Proterozoic Champaner Fold Belt (CFB) Gujarat, Western India. **Journal of Earth System Sciences. https://doi.org/10.1007/s12040-019-1075-z.**
- **Aditya U. Joshi** and M.A.Limaye **(Inpress)** Rootless calc-silicate folds in granite: An implication towards syn to post plutonic emplacement. **Journal of Earth System Sciences. https://doi.org/10.1007/s12040-018-0968-6.**
- **Aditya U. Joshi**, Dhananjay A. Sant, Imtiyaz A. Parvez, Govindan Rangarajan, Manoj A. Limaye, Soumyajit Mukherjee, Mitesh J. Charola, Meghnath N. Bhatt and Sagar P. Mistry **(2018)** Subsurface profiling of granite pluton using microtremor method: southern Aravalli, Gujarat, India. **International Journal of Earth Sciences, vol. 107, pp. 191-201. (DOI: 10. 1007/s00531-017-1482-9).**
- Dhrumil Patel, **Aditya Joshi** and M.A.Limaye **(2016)** Sequential development of microstructures in Quartzites of Champaner Group, Gujarat: An Implication of Godhra Granite. **Journal of Geosciences Research, vol. 1 No. 2, pp. 101-104.**
- **Aditya Joshi** and M.A.Limaye (**2014**) Evidences of Syndeformational granitoid emplacement within Champaner group, Gujarat. **Journal of M.S.U.S.T, vol.49 No. 1, pp.45-54.**

**List of Research Articles (Published/ Accepted) other than Ph.D. Thesis:**

- **Aditya Joshi,** M.A. Limaye and Bhushan S. Deota **(2019)** “Fish-hook” shape intrafolial fold train in quartzite–metapelite band, Lunavada region, NE Gujarat, western India. **International Journal of Earth Sciences, vol. 108, pp. 183-186. (DOI 10.1007/s00531-018-1639-1)**.
- **Aditya Joshi**, M.A.Limaye and Bhushan S. Deota **(2016)** Microstructural indicators of post-deformational brittle-ductile shear zones, Lunawada region, Southern Aravalli Mountain Belt, Gujarat, India. **Journal of M.S.U.S.T, vol. 51 No. 1, pp.19-27.**
- **Aditya Joshi,** M.A.Limaye and Bhushan S. Deota, (**2014**) Structural foot prints extraction from rocks of Lunawada region, Gujarat through IRS LISS III data. **Journal of Geomatics, vol.8 No. 2, pp.170-173.**

- **Aditya Joshi,** M.A.Limaye and Bhushan S. Deota **(2013**) A model representing successive deformational events of Ankalwa Synform, Lunawada Group, Gujarat. **Gondwana.Geological.Magazine, Nagpur, vol.28 No. 1, pp.53-56.**

**Miscellaneous Publications**

- **Photograph of the month (POTM) published in January 2018 (Vol. 91, No.1) of Geological Society of India**: Title of the cover page photo as, "Chiastolite-Andalusite variety encompassing alkali metasomatism within the Champaner Group, Gujarat, western India" authored by, "**Aditya U. Joshi**; M.A.Limaye and Bhushan S. Deota".
- Name in the List of Contributors in **Atlas of Structural Geology (Elsevier, 2015).**

**List of Conferences Attended as well as Presented:**

- 5th Conference and Workshop on Rock Deformation and Structures (RDS-V); held at Department of Geology, University of Delhi, Delhi, from 4th to 6th October, 2018.

  **Title of Work:** 1. Mantled opaque porphyroclasts and fishes employed as a shear sense indicator: A microstructural study along Narukot Shear Zone (NSZ), Champaner Group, Eastern Gujarat

  Authored by: **Aditya U. Joshi**, Soumyajit Mukherjee and M.A.Limaye

  **Title of Work:** 2. Shear induced folds: An example from Lunavada Group, Southern Aravalli Mountain Belt (SAMB), Gujarat

  **Authored by:** M. A. Limaye, **Aditya U. Joshi,** Bhushan S. Deota.
- **Science Conclave 2017**; held at the Faculty of Science, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, on 28th Feb 2017.

  **Title of Work:** Opaque, an uncommon porphyroclast used as a shear sense indicator: A microstructural study along Narukot and Khandia Shear Zone within the Champaner Fold Belt, Gujarat, western India.

  **Authored by: Aditya Joshi**, Soumyajit Mukherjee and M.A.Limaye.
- **DST PURSE Sponsored National Seminar on Recent Scenario in Science and Technology (RSST-2016)**; held at the Faculty of Technology and Engineering, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, on 27th Feb 2016.

  **Title of Work:** Characterization of Low grade Iron Ore from Rajasthan.

  **Authored by:** Yakshil Chokshi, S.K.Dutta, M.A.Limaye and **Aditya Joshi.**
- **XXX Gujarat Science Congress – 2016 on 'Challenges for Science and Technology Education During Coming Decades: Preparing for a**

**Sustainable Gujarat'** Jointly organized by K.S.K.V Kachchh University and Gujarat Science Academy; held at K.S.K.V Kachchh University on 6th and 7th Feb 2016.

**Title of Work:** 1. Microstructural studies of phyllites from Narukot region, Champaner Group, Gujarat.

**Authored by: Aditya Joshi** and M.A.Limaye.

**Title of Work:** 2. Rootless folds over granites: An example from Lambia Formation, Champaner Group, Gujarat.

**Authored by:** M.A.Limaye, **Aditya Joshi** and Bhavesh Sharma.

- **Developments in Geosciences in the past decade- emerging trends for the future and impact on society and Annual General Meeting of the Geological Society of India**; held at the Indian Institute of Technology Kharagpur (India) from 21st to 23rd Oct 2016.

  **Title of Work:** 1. Granite induced deformation: An example of superposed folding from Lambia Formation, Champaner Group, SAMB, Gujarat.

  **Authored by: Aditya Joshi** and M.A.Limaye.

  Title of Work: 2. Microstructural investigation along contact aureole A case study from Narukot Formation, Champaner Group, Gujarat, India

  **Authored by:** M.A.Limaye and **Aditya Joshi**.

- **National Geo-Research Scholars Meet 2016**; held at Wadia Institute of Himalayan Geology, Dehradun from 1st to 4th June 2016.

  **Title of Work:** Studies on phyllites of Narukot Formation, Champaner Group, Gujarat: A microtectonic approach.

  **Authored by: Aditya Joshi** and M.A.Limaye.

- **GUJCOST sponsored one day National Seminar on Ethics and Plagiarism in Academic Research (EtPAR – 2015)**; Organised by Pharmacy Department, Faculty of Technology and Engineering, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat on 24th Aug 2015.

- **XXIX Gujarat Science Congress – 2015**; organized by Gujarat Science Academy; held at Science City, Ahmedabad on 28th Feb and 1st March 2015.

  **Title of Work:** 1. Structural disposition of Godhra granitoid emplacement within Champaner Group, Gujarat.

  **Authored by: Aditya Joshi** and M.A.Limaye.

  **Title of Work:** 2. A study on quartzites of Champaner Group, Gujarat: An implication of Godhra granitoid.

  **Authored by:** M.A.Limaye, **Aditya Joshi** and Dhrumil Patel.

- **National Seminar on Rock Deformation and Structures (RDS – III)**; Under the aegis of Structural Geology and Tectonic Studies Group – India; Organised by Department of Applied Geology, Dibrugarh University, Assam, from 29th to 31st Oct 2014.

  **Title of Work:** 1. Evidences of Coaxial deformation from Narukot area, Champaner Group, Eastern Gujarat.

  **Authored by: Aditya Joshi** and M.A.Limaye.

  **Title of Work:** 2. Microstructural and Crystal Size Distribution (CSD) studies on quartzites of Champaner Group, Gujarat.

  **Authored by: Aditya Joshi**, M.A.Limaye and Dhrumil Patel.

- **International Seminar on Magmatism, Tectonism and Mineralization (MTM – 2014)**; held at Department of Geology, Centre of Advance Study, Kumaun University, Nainital, Uttarakhand, India, from 27th to 29th March 2014.

  **Title of Work:** A new record of Alkaline Igneous intrusive activity from Champaner Group (SAFB), Gujarat, India: Its Tectonomagmatic Implications.

  **Authored by:** M.A.Limaye, Rohit Pandey and **Aditya Joshi**.

- **3rd International conference on Precambrian Continental Growth and Tectonism PCGT – 2013**; Organised by Department of Geology, Bundelkhand University, Jhansi, India, from 23rd to 26th Nov 2013.

  **Title of Work:** Microstructural indicators of Khajuriya fault, SE of Lunawada, Gujarat.

  **Authored by: Aditya Joshi**, M.A.Limaye and Bhushan S. Deota.

- **26th Annual Conference of Indian Institute of Geomorphologists (IGI) on 'Dynamics of Earth Surface Processes'**; Jointly organised by Department of Geography and Department of Geology, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, from 20th – 22nd Nov 2013.

  **Title of Work:** Geomorphic Expression of Plastic and Brittle Deformation within Lunawada Group of rocks, Gujarat, India.

  **Authored by: Aditya Joshi**, M.A.Limaye and Bhushan S. Deota.

- **Geoyouth – 2013** '4th All India Symposium on Geology'; held at Department of Geology, Mohanlal Sukhadia University, Udaipur, Rajasthan, on 15th and 16th Feb 2013.

  **Title of Work:** Time relationship between Metamorphism and Deformation in Proterozoic rocks of Kadana Formation, north of Lunawada, Gujarat.

  **Authored by: Aditya Joshi**.

**List of Workshops attended:**

- **Workshop on Scientific Skills: Writing Manuscript, Project Proposal, Oral and Poster Presentation**; Organised by Chemical Engineering Department, Faculty of Technology and Engineering, The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, on 3rd March 2014.
- **DST Sponsored Training Programme on Construction of Balanced Cross Sections and Structural Profiles in Deformed Terranes**; Organised by Department of Applied Geology, Dibrugarh University, Assam, on 31st Oct 2014.
- **Refresher Course on Structural Geology**; Conducted by **Government of India**, **Geological Survey of India**, Regional Training Institute, Western Region, held at Zawar, Rajasthan, from 6th to 15th Jan 2015.
- **International Union of Geological Sciences commission on Tectonics and Structural Geology (IUGS – TecTask) sponsored workshop – 1: Mohr Circle Simplified; 2. Modern Methods of Fabric Analysis in Deformed Rocks**; held at Indian Institute of Technology Kharagpur, India, from 21st – 23rd Oct 2016.
- **National Workshop on Digital Mapping;** held at Department of Geology, University of Delhi, Delhi, on 6th October, 2018.

**Awards and Recognitions**

- Invited as a **Teaching Faculty** to participate in the one day field trip to Champaner, Vadodara district on 20th January 2018, with more than 100 executives and members of **Association of Petroleum Geologists (APG) and Society of Petroleum Geophysicists (SPG); Organised by Oil and Natural Gas Corporation (ONGC).**
- Invited as a **Young Researcher Faculty** to conduct one day structural field workshop on 18th March 2017, for the post graduate students of **Department of Earth Sciences, Goa University.**
- **Best presentation award in Science Conclave 2017** in Earth Science category on 28th Feb 2017, held at the Faculty of Science, **The Maharaja Sayajirao University of Baroda, Vadodara. 390002. Gujarat.**
- **Best Paper and Presentation award in Geoyouth-2013** ‘4th All India students symposium on Geology’ from 15th Feb to 16th Feb 2013, held at **Department of Geology, Mohanlal Sukhadia University, Udaipur, Rajasthan.**

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# Fold interference patterns in Meso-Proterozoic Champaner fold belt (CFB) Gujarat, western India

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This paper documents three phases of folding within the Meso-Proterozoic Champaner Fold Belt (CFB) located at the eastern part of Gujarat, western India. The first phase ($F_1$) displays WNW plunging $F_1$ fold of moderately inclined nature in the schists of the Khandia Formation. The second phase ($F_2$) refolded $F_1$ along a similar trend to produce folds of tight isoclinal nature in the Khandia and Narukot quartzites. Additionally, these $F_1$ folds depict second-order tight, and $F_2$ folds as first-order open type in the younger sequences of the CFB with varying amplitude *vs.* wavelength ratio. The ratio for $F_1$ folds ranges from 2:1 to 3:1, obtained along 3–4 m length across 3–6 $m^2$ area, whereas for $F_2$ folds the ratio ranges from 1:4 to 1:5 and is obtained along 1–2.5 km length across 0.5–1.5 $km^2$ area. The fold interference pattern developed on account of $F_1$ and $F_2$ folds has resulted into Type-III or hook-shaped geometry regionally. The last phase of folding is characterised by N–S trending $F_3$ folds of open type over kilometre long limbs of $F_1$ and $F_2$ folds. The superposition of $F_{1-3}$ folds developed map scale Type-I or Dome and Basin geometry over Type-III superposed folds. The overall compressional direction for $F_1$ and $F_2$ folds ranges from N–S to NNE–SSW and for $F_3$ ranges from E–W to ESE–WNW.

**Keywords.** Champaner Fold Belt (CFB); Narukot; interference fold pattern; hook shaped; dome and basin.

## 1. Introduction

In any area, the existence of interference fold patterns indicates refolding of earlier folds. A derivative of these interference geometries ranges from micro- to mega-scale (see, e.g., Platt 1983; Ghosh 1993; Fossen and Holst 1995; Mamtani *et al.* 2001; Caritg *et al.* 2004; Tian *et al.* 2013; Fossen 2016). The interference geometries are important as they provide significant clues on shortening direction and decode the multiple deformational events (Forbes and Betts 2004; Forbes *et al.* 2004). A combination of such refolded folds on map scale has been documented in the present work with the aid of detailed fieldwork.

The area under investigation is the part of Southern Aravalli Mountain Belt (SAMB) exposed along the eastern fringe of Gujarat, India (figure 1a). Rocks of this region belong to the Champaner Group of Meso-Proterozoic age, forming the youngest part of the Aravalli Supergroup (Gupta *et al.* 1992, 1995, 1997). Initially, the structural history of the Champaner Group was thought to be very simple with respect to the main Aravalli domain. The idea proposed by Roy (1985, 1988) and Merh (1995) suggests that the Champaner

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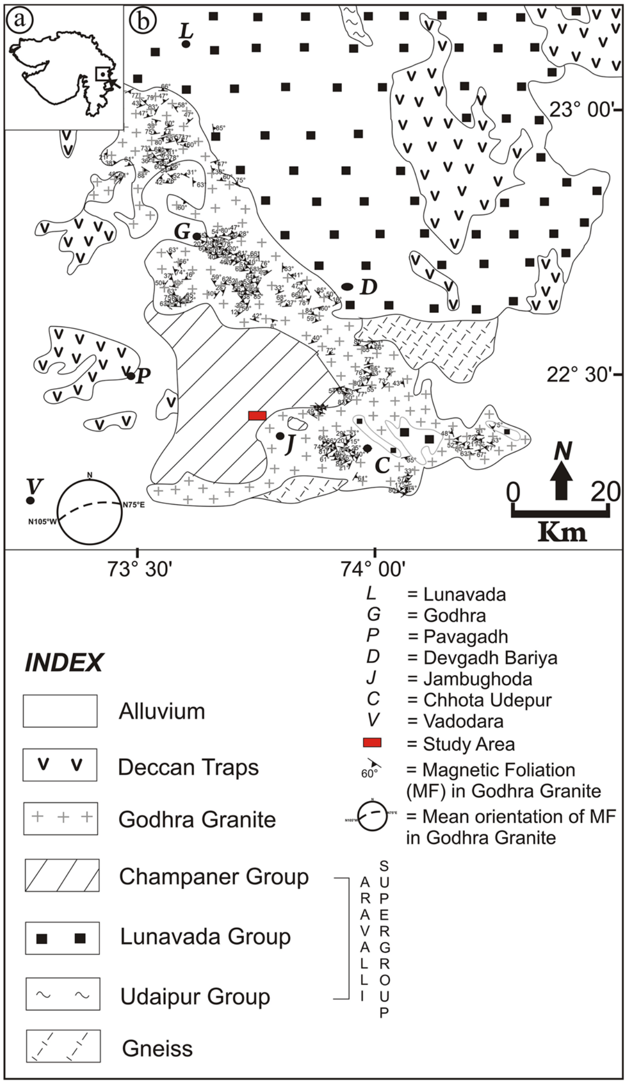


Figure 1. (**a**) Location sketch of the Champaner Group; (**b**) lithostratigraphic map of SAMB, NW, India. Modified after Mamtani and Greiling (2005). Red square indicates the study area. Magnetic foliation data presented within Godhra granite is after Mamtani (2014).

Group represents one single phase of deformation and possesses no superposed folds. Later on the detailed work carried out by Karanth and Das (2000) and Das (2003) in order to decode the deformational history of the Pre-Champaner Gneissic Complex in Chhota Udepur region gave a comparative study about the deformational style between Pre-Champaners and Champaner rocks. They illustrated two phases of folding within the Champaner Group having orthogonal axial planes. However, they did not comment on the existence of superposed folds within the Champaner Group of rocks, unlike that in the Pre-Champaner Gneissic Complex of Chhota Udepur region. In the light of hitherto work, more research is needed in order to address the structural complexity in the form of interference fold pattern within the rocks of the Champaner Group.

## 2. Geological setting

The Champaner Fold Belt, consists of the Champaner Group, is a part of upper Aravalli exposed along the southern most fringe of SAMB in Gujarat (Gupta *et al.* 1992, 1995) (figure 1b). The Champaner Group is characterised by Meso-Proterozoic low-grade metasedimentary rocks and are intruded by Neo-Proterozoic (955±20 Ma) Godhra granite (Rb/Sr method; Gopalan *et al.* 1979). Lithologically, it comprises metasubgraywacke, phyllite, carbonaceous schist, quartzite, gneisses and petromict metaconglomerate with bands of dolomitic limestone and mangeniferous phyllite (Gupta *et al.* 1980, 1997) (figure 2a). Based on the homogeneity in terms of rock type, strike persistency and occurrence of intraformational conglomerate, the Champaner Group has been divided into six formations (Gupta *et al.* 1997) (table 1; Gupta *et al.* 1980, 1992). Greenschist facies condition demarcates the regional grade of metamorphism, whereas the contact metamorphic grade has reached up to the hornblende hornfels facies (Jambusaria and Merh 1967; Jambusaria 1970; Gupta *et al.* 1997; Das 2003; Das *et al.* 2009).

## 3. Structural setup

The existing structural set up of the Champaner Group suggests that the rocks are polydeformed forming a regional 'S' shaped pattern consisting two major anticlines and synclines (Jambusaria 1970). Two phases of deformation have been recorded so far, viz., $D_1$: E–W trending $F_1$ folds of tight/isoclinal upright nature; and $D_2$: N–S trending $F_2$ folds with N plunging open warps with kink bands (Jambusaria and Merh 1967; Gopinath *et al.* 1977; Shah *et al.* 1984; Srikarni and Das 1996; Karanth and Das 2000; Das 2003; Limaye and Bhatt 2013; Limaye 2016a, b; Patel *et al.* 2016). $F_1$ and $F_2$ folds are also affected by numerous axial planar slippages depicting radial pattern (Jambusaria and Merh 1967; Yellur 1969; Jambusaria 1970; Joshi *et al.* 2018). The axial planar slippages scattered in a radial pattern show signatures of sinistral/dextral faults (figure 2a). Moreover, there also exists signature of top-to-east cross-sectional

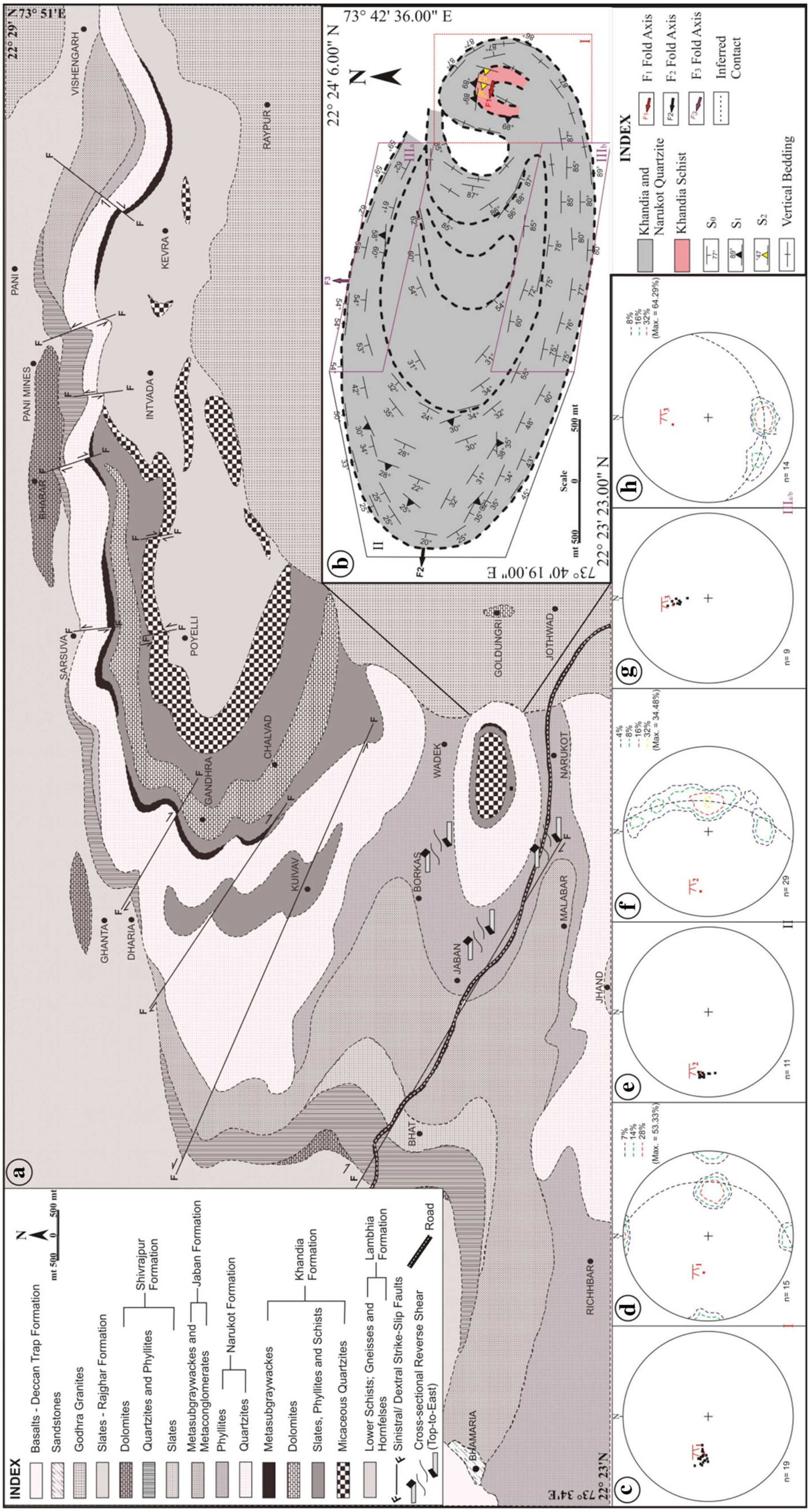


Figure 2. (**a**) Geological map of the Champaner region, modified after Jambusaria (1970), Gupta *et al.* (1997) and Joshi *et al.* (2018); (**b**) detailed structural map of the Narukot dome; (**c**) sub-area I: lower hemisphere stereographic projection of the $L_2$ ($S_2$–$S_0$) intersection lineation data collected from $F_1$ dominated area. The $\pi_1$ axis of $F_1$ fold (red triangle) orientation fits well with the pucker axes lineations measured in the field (filled square); (**d**) contoured Pie diagram of sub-area I showing $F_1$ fold axis ($\pi_1$): $n = 15$, $S_0$; contours = 7%, 14%, 28% per unit area; (**e**) sub-area II: stereographic projection of the $L_2$ intersection lineation (secondary cleavage planes and $S_0$) data collected from $F_2$ dominated area. The $\pi_2$ axis of $F_2$ fold (red triangle) orientation fits well with intersection lineations measured in the field (filled square); (**f**) contoured Pie diagram of sub-area II showing $F_2$ fold axis ($\pi_2$): $n = 29$, $S_0$; contours = 4%, 8%, 16%, 32% per unit area; (**g**) sub-area $III_{a\ and\ b}$: lower hemisphere stereographic projection of steeply plunging $F_3$ fold axis collected from the field. The $\pi_3$ fold axis (red triangle) matches with the field lineations of $F_3$ fold axis (filled square); and (**h**) contoured Pie diagram of sub-area $III_{a\ and\ b}$ showing $F_3$ fold axis ($\pi_3$): $n = 14$, $S_0$; contours = 8%, 16%, 32% per unit area.

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

| Proterozoic stratigraphic succession of Gujarat and South Rajasthan | | |
|---|---|---|
| Proterozoic | Malani igneous suite<br>Erinpura granite<br>Godhra granite | Intrusives post-Delhi |
| | Punagarh group<br>Sirohi group<br>Sendra Ambaji granite and gneiss<br>Phulad ophiolite suite<br>Kumbhalgarh group<br>Gogunda group | Delhi super group |
| | Champaner group - Rajgadh formation<br>Shivrajpur formation<br>Jaban formation<br>Narukot formation<br>Khandia formation<br>Lambia formation<br>Lunavada group<br>Synorogenic granite and gneiss<br>Rakhabdev ultramafic suite<br>Jharol group<br>Bari lake group<br>Udaipur group<br>Debari group | Aravalli super group |
| Archaean | Basement complex | Bhilwara super group |

Gupta *et al* (1980, 1992)

reverse shears within the rocks of the Narukot Formation (figure 2a) (Joshi *et al.* 2018). A combination of $F_1$ and $F_2$ folds along the E margin of the Champaner Group has generated interesting dome structures at Narukot and Poyli areas (Jambusaria 1970). One such dome 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. Dome appearance at Narukot is composed of the combination of $F_1$ to $F_3$ folds regionally (figure 2b). In order to carry out the structural analysis the area has been divided into sub-areas, i.e., I, II, $III_a$ and $III_b$, representing $F_1$, $F_2$ and $F_3$ dominated regions, respectively. Sub-area I represents $F_1$ fold with an axial trace dipping due WNW


Figure 3. (**a**) $L_2$ ($S_2$–$S_0$) intersection lineation in schist of Khandia Formation (camera faces southern direction); (**b**) sub-parallel relationship between $S_0$ and $S_1$ in quartzite demarcated over the outcrop with black pen markings. Discrete secondary cleavages can be appreciated over $S_0$ (camera faces southeastern direction); (**c**) steep F3 fold axes preserved in quartzite (camera faces southern direction); (**d**) second-order tight $F_1$ folds in phyllite of Shivrajpur Formation (camera faces western direction); (**e**) second-order tight $F_1$ folds within the right limb of first-order open $F_2$ fold in quartzite of Shivrajpur Formation (camera faces western direction); (**f**) second-order tight $F_1$ fold in quartzite of Lambhia Formation (camera faces western direction); (**g**) first-order $F_2$ fold in quartzite of Rajghar Formation (camera faces eastern direction); (**h**) N–S trending Kink band in phyllite of Narukot Formation (camera faces northern direction); (**i**) field photograph after Joshi and Limaye (2014), showing discordant relationship between intruding coarse-grained granite into fine-grained granite (camera faces eastern direction); (**j**) xenolith of schistose rock within granite (camera faces western direction); (**k**) xenolith of fine-grained granite in coarse-grained granite (camera faces northern direction); (**l**) sharp intrusive contact between granite and the Champaner metasediments (camera faces eastern direction); (**m–p**) top-to-east ductile shear along the cross-section. S schistosity fabric dipping steeper than the C-plane. Photograph (**n–p**) after Joshi *et al.* (2018).

in Khandia schist located at the eastern part of the dome. $F_1$ fold has resulted due to folding of $S_0$ bedding plane by generating $S_1$ schistosity plane. Due to the manifestation of $F_2$ over $F_1$, $S_0$ shows sub-parallel relationship with $S_1$ and axial planar $S_2$ schistosity plane has been developed generating $L_2$ lineations on $S_0$ (figure 3a). These lineations are intersection lineations formed by $S_2$–$S_0$ intersection, which plunges 46° in the direction of 279°N and form pucker axis over the hinge line. By plotting several such lineations over lower hemisphere stereographic projection, the orientation of $\pi_1$ axis fits well with the pucker axes lineations obtained from the field (figure 2c). The fold is moderately inclined having pitch of the $F_1$ fold axis 47° in the direction of 280°N (WNW) measured on $S_0$ plane (figure 2d). Tight to isoclinal $F_2$ folds affected quartzite band as $F_1$ folds refolded along a 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 $S_1$ (figure 3b). $S_2$ orientation is feeble and mostly appears as discrete cleavages to form $L_2$ intersection lineations between secondary cleavage planes and $S_0$ over $S_1$. $\pi_2$ axis of $F_2$ fold matches with the data set of intersection lineations recorded from $F_2$ dominated area (figure 2e). The core of the $F_2$ fold is traceable for 1 km at the western margin of the Narukot dome and can be seen in sub-area II of figure 2b. 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° and possess a sub-vertical axial plane (figure 2f). Sub-area $\text{III}_{a,b}$ depicts $F_3$ open fold trending N–S axial trace over kilometre long limbs of $F_1$ and $F_2$ folds. The axial plane can be traced from the N to the S fringe of the dome dividing it into two approximately equal portions. Steeply dipping mesoscopic $F_3$ fold axes have been observed along outer rim of quartzite near SW of Wadek (figure 3c). These lineations fit well with the fold axis $\pi_3$ (figure 2g). The folds possess vertical axial plane and have a northerly plunge of its axis (figure 2h). Representation of $F_{1-3}$ folds along with the orientation of the axial plane and fold axis in the Narukot dome, depicted by SRTM worldwide elevation data (3-arc-second resolution) downloaded from Global mapper (v17) (figure 4).

An attempt has been made to study the derivates of these three fold events across the Champaner Group. The results signify that further to the W of the Narukot dome, where the younger Formation of the Champaner Group is encountered, $F_1$ folds exhibit second-order tight and $F_2$ folds as first-order open with varying amplitude *vs.* wavelength ratio (figure 3d–g). 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 m length across 3–6 $m^2$ 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 $m^2$ area. These $F_2$ fold ratios have been acquired through satellite image and validated during mapping. $F_3$ folds gradually die out in the form of mega-scale open wraps to meso-scale kink bands from eastern to the western stretch of the Champaner Group, respectively (figure 3h).

## 4. Discussions

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) and Ramsay and Huber (1987), demonstrating a comprehensive hammer head anticlinal structure. Their fold axes are sub-parallel ($F_1\sim$ WNW; $F_2\sim$ 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 (locations in figure 2a).

In order to postulate the possible causes of the fold trends recorded from the Champaner Group, the proto-continent accretion concept (primarily given by Naqvi *et al.* 1974; Radhakrishna and Naqvi 1986; Rogers 1986; Naqvi and Rogers 1987) for the Aravalli, the Dharwar and the Singhbhum proto-continents proved to be useful. The 'Y'-shaped lineaments, viz., the Narmada, Son and Godavari, along which the Aravalli–Dharwar, the Aravalli–Singhbhum and the Dharwar–Singhbhum proto-continents accreted, respectively, during the Meso-Proterozoic times. Based on a 'Working Model' or 'Working Hypothesis' given by Mamtani *et al.* (2000) in terms of deformation pertaining to the SAMB it clearly suggests that, there is an impact of accretionary event on southern part of the Aravalli proto-continent the manifestation of which is in the form of changes in the structural trends and growth of metamorphic minerals. Further the model illustrates that the E to NW trending structures in SAMB formed suturing between the Aravalli and the Dharwar Protocontinents (ca. 1400–935 Ma). In case of the present study, the N–S to NNE–SSW shortening direction generated on account of the suturing has led to the development of ESE–WNW to E–W trending structures across the Champaner Group. Furthermore, the area located at the core of the

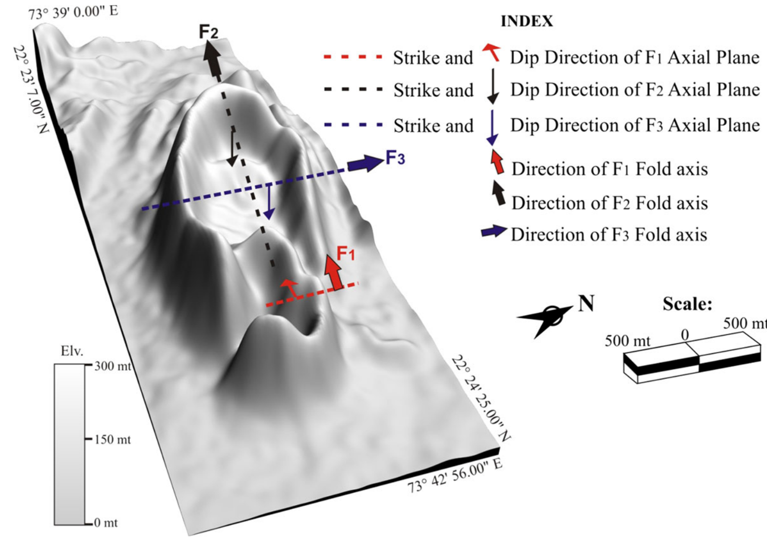


Figure 4. SRTM-derived shaded relief map of the Narukot Hammer head anticlinal structure. Respective orientations of the axial planes and fold axis have been demarcated.

Champaner Group has experienced intense compression due to regional deformation, engendering refolding of earlier folds at the Narukot dome and imparting westerly plunge to $F_1$ and $F_2$ folds (figure 5a). Similar concept of protoplate tectonics has been anticipated to explain the deformational patterns observed in the southern parts of the Delhi Fold Belt (by Sychanthavong and Desai 1977; Sychanthavong and Merh 1981, 1985; Sychanthavong 1990).

Granites located in and around the Champaner Group of rocks display signatures of syn to post-plutonic emplacement (Joshi and Limaye 2018). Distinguishing characteristic of syn/post-tectonic granite can be very well appreciated along the east of the Jhand area (location presented in figure 2a), where coarse-grained post-tectonic granite is having intrusive relationship with the fine-grained syn-tectonic granite (figure 3i) (Joshi and Limaye 2014). The coeval pulse of granite emplaced during progressive deformation has magnetic foliation trending WNW–WSW (figure 1b). 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 (figure 5a) (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 (figures 2a and 5b). 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 is found to be developed along the eastern margin of the Champaner Group bordering the pluton. SRTM-derived shaded relief map of the Champaner region demarcates folded metasediments and its relationship with the adjacent pluton (figure 6). The post-tectonic granite having the geochemical affinity of 'A-type' representing transitional or post-orogenic uplift (suggested by Maithani *et al.* 1998 and Goyal *et al.* 2001), has been intruded by accommodating the space within the Champaner metasediments and pre-existing syn-tectonic pulse (figure 5b). Such inference has been derived by collecting xenolith evidence of (i) Champaner metasediment and (ii) fine-grained granite from coarse-grained granite variety (figure 3j–k). One such location is at the northeastern fringe of the Champaner region near Sukhi dam, where intrusive contact between Godhra granite and Champaner metasediments is exposed (figure 3l).

Geophysical studies carried out by Joshi *et al.* (2018) using Microtremor method suggests pluton hump exactly below the Narukot dome. The surface manifestation of pluton hump can be corroborated by the development of the cross-sectional reverse shear having top-to-east shear

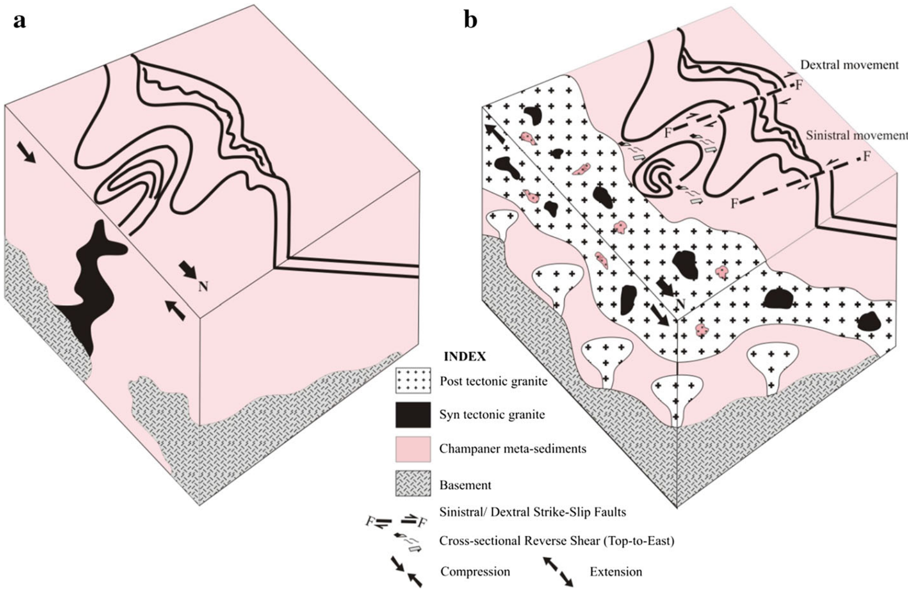


Figure 5. (**a**) Cartoon showing suturing of proto-continents and refolding of earlier folds along with the plunge on account of regional deformation as well as emplacement of syntectonic granite; (**b**) closing up of earlier refolded folds orthogonally and development of sinistral/dextral faults along the pre-existing axial planes due to post-intrusive pulse. Granite of post-tectonic nature holds xenoliths of Champaner metasediments and earlier syn-tectonic granite. These cartoons have been modified after Winter (2012).

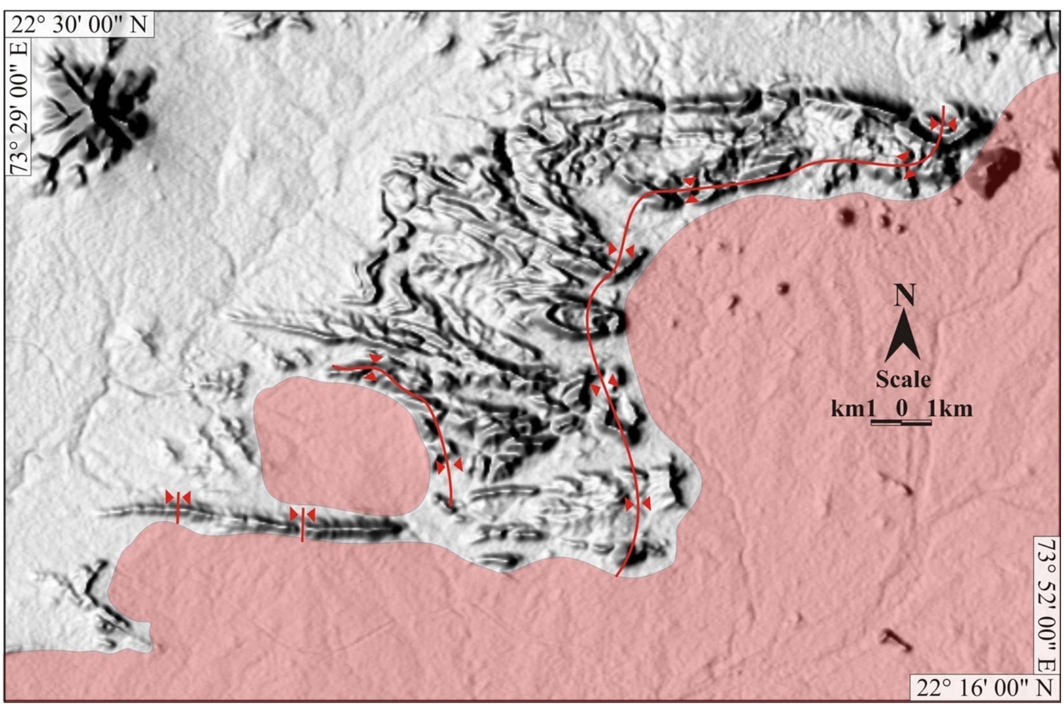


Figure 6. SRTM-derived shaded relief map of the Champaner region. Red region demarcates the granite country and shades of grey depict the folded Champaner metasediments. Curved thin red line shows the axial trace of the rim synclines developed along the periphery of the granite pluton.

sense, in the vicinity of the Narukot dome (figure 3m–p). Recent work carried out by Joshi and Limaye (2018) at Jothwad region on isolated calc-silicate bands from khandia Formation records signatures of out-of-sequence deformation due to post-tectonic granite. The Jothwad region, part of the Champaner Group, represents superimposition of Type-II interference pattern over cylindrical

Table 2. *Summarisation of various interference fold patterns along with the fold and fault events observed within the Champaner Group (data of out-of-sequence deformation is after Joshi and Limaye 2018).*

| Intrusives | | Deformation | Interference Fold Patterns and Fault Events | |
|---|---|---|---|---|
| Granite Emplacement | | | *In Sequence* | *Out-of-Sequence* |
| | Syn | Regional | **Type-III**<br>F1 ~ ESE-WNW;<br>F2 ~ E-W Plunging Folds | **Cylindrical Upright Fold**<br>F1 ~ NW-SE to N-S |
| | Post | Granite Induced | **Type-I**<br>F3 ~ N-S;<br>Sinistral/ Dextral Faults;<br>Cross-sectional reverse shear (top-to-east) | **Type-II**<br>F2 ~ NE-SW |

upright fold. Moreover, these interference fold patterns are rootless and depict no continuity in the subsurface as well as are unmatched with the existing structural set up of the Champaner Group.

## 5. Conclusions

- The Meso-Proterozoic Champaner Group represents interference fold patterns ranging from Type-1 to Type-III (table 2).
- Type-III interference fold pattern is due to regional deformation and generated by combinations of $F_{1-2}$ folds ($F_1\sim$ ESE–WNW; $F_2\sim$E–W).
- Regional deformation has imparted westerly plunge to $F_{1-2}$ folds and also characterised by syn-tectonic emplacement of granite having similar trend.
- Type-I interference pattern superimposed over Type-III by closing up of domes, represents $F_3$ folds ($F_3\sim$ N–S) due to post-intrusive granite. The same has been responsible for the development of sinistral/dextral faults throughout the group and cross-sectional reverse shears in vicinity of the Narukot dome.
- Type-II superimposed over rootless cylindrical upright folds represents out-of-sequence deformation of $F_{1-2}$ folds ($F_1\sim$NW–SE to N–S; $F_2\sim$ NE–SW) suggests syn-post plutonic emplacement.

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# 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: $D_1$, persistent throughout the group and characterised by westerly plunging tight isoclinal folds and $D_2$, 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-Chamapaner 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

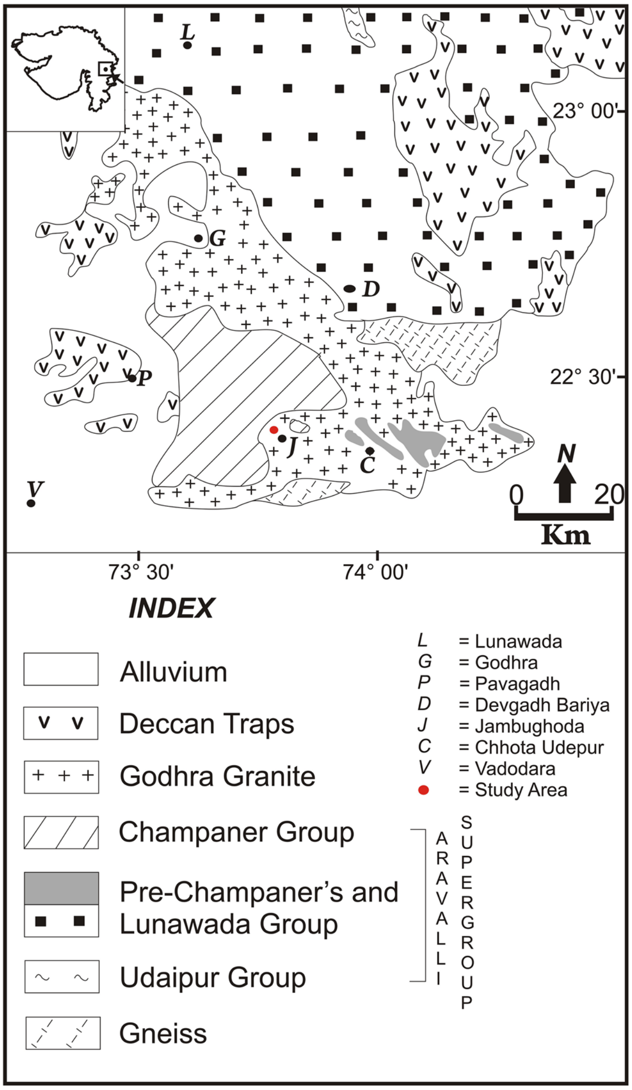


Figure 1(**a**). Lithostratigraphic map of Southern Aravalli Mountain Belt, NW, India (modified after Mamtani and Greiling 2005).

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 manganiferous 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., $D_1$ and $D_2$. $D_1$ 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. $D_2$, 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 $D_1$ 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 $D_1$ axial planar strike slip faults and shear zones across the Champaner Group (Joshi *et al.* 2018). Due to the heterogeneity in terms of manganiferous 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 prolong 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 $D_1$ deformation of the Champaner Group of rocks.

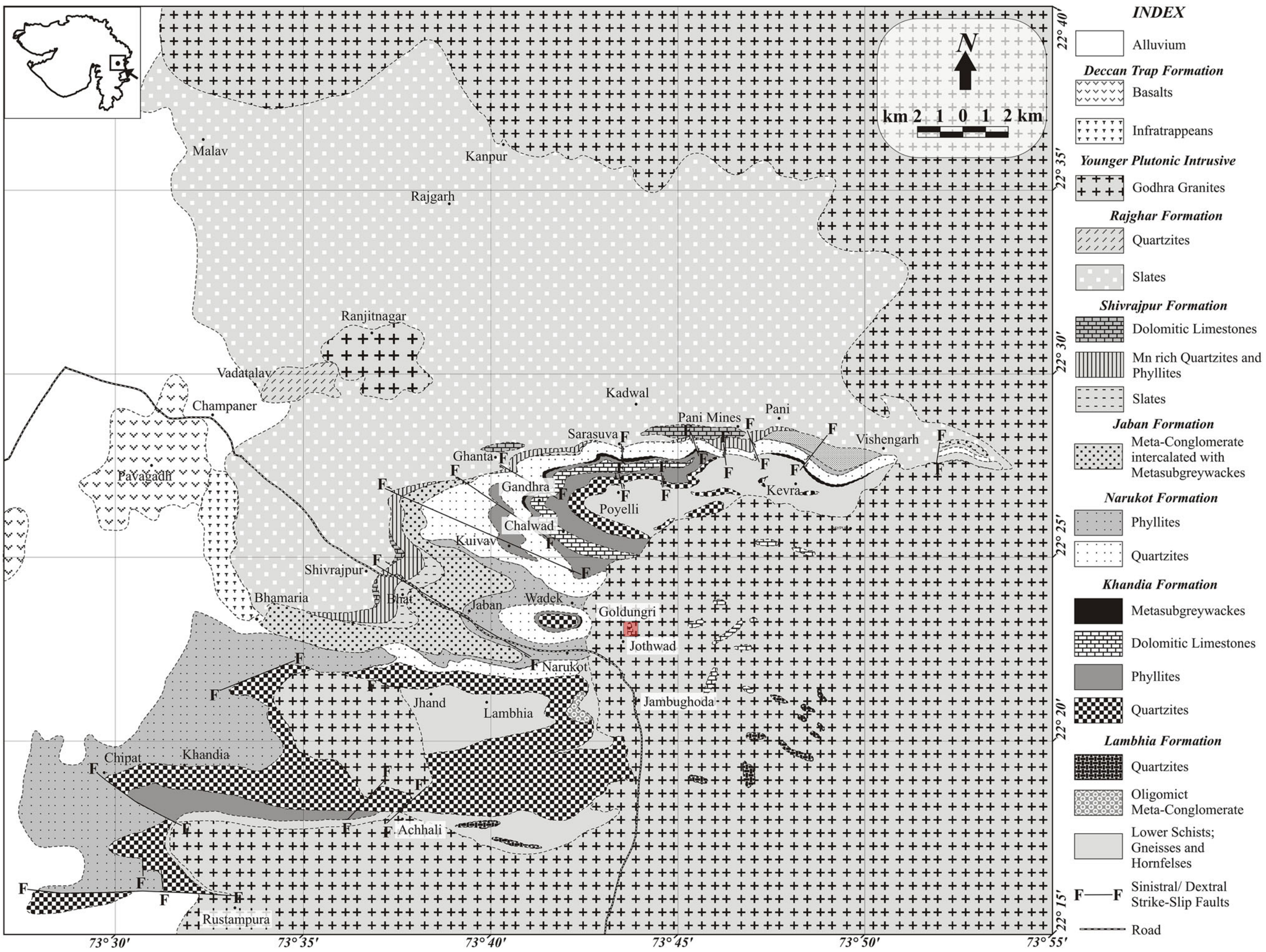


Figure 1**(b)**. Generalized geological map of the Champaner Group and neighbouring areas (modified after Jambusaria and Merh 1967 and Gupta *et al.* 1997). Filled red square indicates the study area.

## 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, piedmontite 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 | | |
|---|---|---|
| PROTEROZOIC | Malani Igneous Suite<br>Erinpura Granite<br>Godhra Granite and Gneiss | Post-Delhi Intrusives |
| | Punagarh Group<br>Sirohi Group<br>Sendra Ambaji Granite and Gneiss<br>Phulad Ophiolite Suite<br>Kumbhalgarh Group<br>Gogunda Group | Delhi SuperGroup |
| | Champaner Group - Rajgadh Formation<br>Shivrajpur Formation<br>Jaban Formation<br>Narukot Formation<br>Khandia Formation<br>Lambia Formation<br>Lunavada Group<br>Synorogenic Granite and Gneiss<br>Rakhabdev Ultramafic Suite<br>Jharol Group<br>Bari lake Group<br>Udaipur Group<br>Debari Group | Aravalli SuperGroup |
| 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° 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° 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).

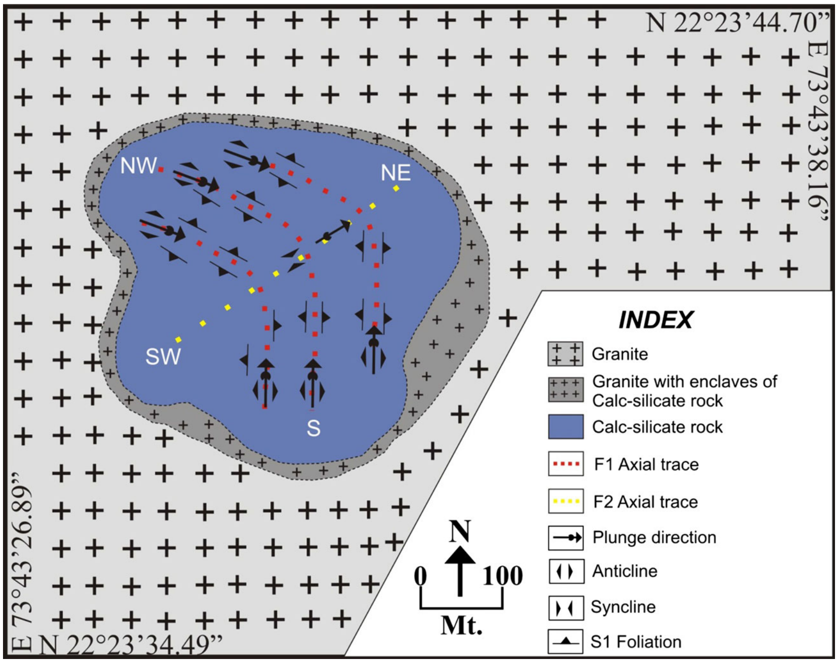


Figure 2. Geological map of the Jothwad region (study area).

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 Devgadh 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

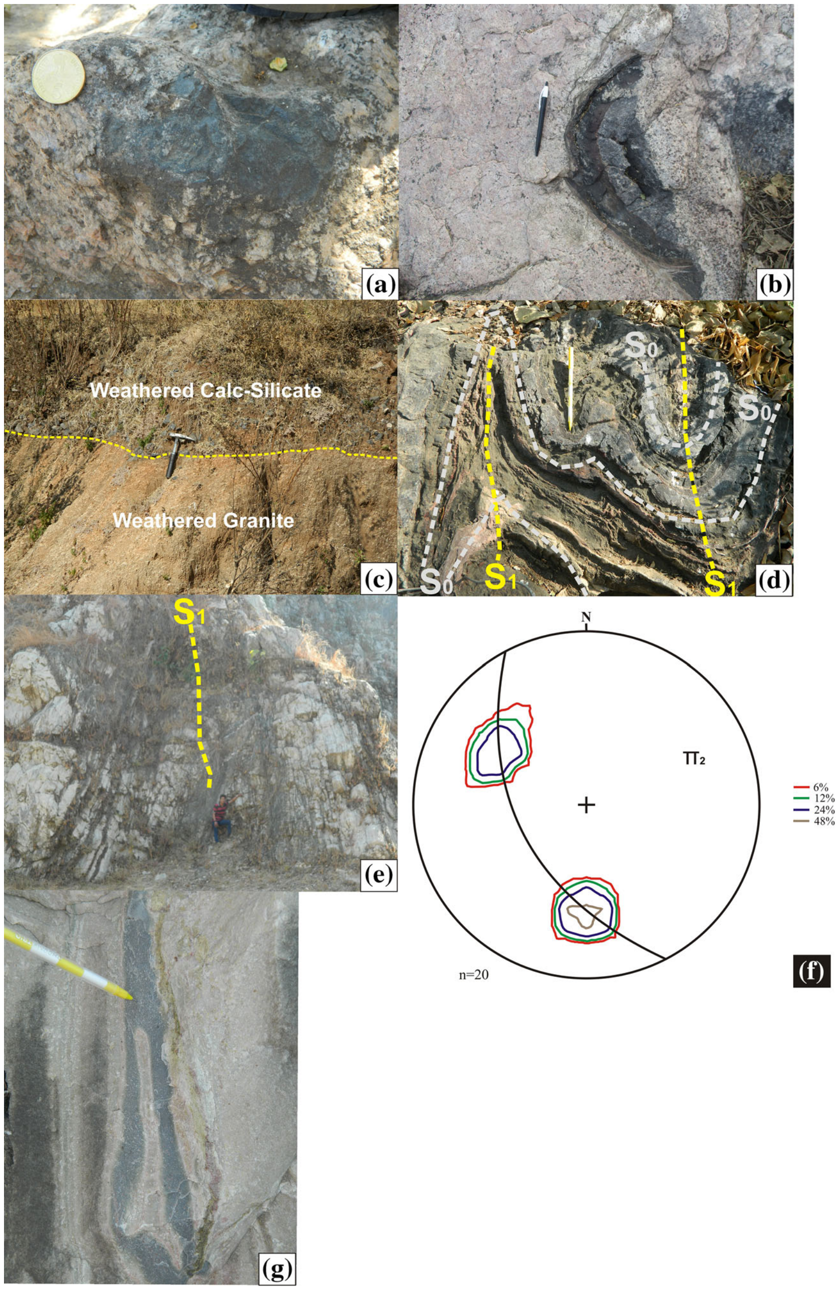


Figure 3. (**a**) Enclaves of calc-silicate rock in granite (camera faces in eastern direction); (**b**) Caught up folded fragment of calc-silicate rock embedded in granite (camera faces in southeastern direction); (**c**) Dotted line demarcates inferred contact between weathered calc-silicate rock and 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 ($\pi_{II}$) 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 Devgadh 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 | – | – | – |
| **$D_3$ having axial trace trend ESE–WNW to ENE–WSW** | **$D_3$ having axial trace trend E–W to NW–SE** | **$D_2$ and $D_3$ having axial trace trend E–W with different fold morphology (a. Recline and b. Upright)** | **$D_1$ 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 $D_3$ deformation of the Lunavada region. Microstructural records specify advent of thermal event related to late $D_3$/post-$D_3$ Godhra granitic intrusion in the Lunavada terrain (Mamtani and Karanth 1996; Mamtani *et al.* 2001). Based on which, a possibility can be determined that $D_3$ deformation of the Lunavada region and $D_1$ 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 $D_1$ 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 $D_1$ 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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ORIGINAL PAPER

# Subsurface profiling of granite pluton using microtremor method: southern Aravalli, Gujarat, India

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**Abstract** We report, using the microtremor method, a subsurface granitic pluton underneath the Narukot Dome and in its western extension along a WNW profile, in proximity of eastern fringe of Cambay Rift, India. The dome and its extension is a part of the Champaner Group of rocks belonging to the Mesoproterozoic Aravalli Supergroup. The present finding elucidates development of an asymmetric double plunge along Narukot Dome. Microtremor measurements at 32 sites were carried out along the axial trace (N95°) of the dome. 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 $\geq$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 proposed equation describing frequency–depth relationship between granite and overlaying regolith matches with those already published in the literature. The morphology of granite pluton highlights the rootless character of Champaner Group showing sharp discordance with granitic pluton. The findings of manifestation of 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.

**Keywords** Microtremor · H/V spectral analysis · Granite pluton · Champaner group · Aravalli

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## Introduction

Neoproterozoic granites in this study popularly referred to as Godhra granite, constitute a part of major syn- to post-orogenic granitic phase of southeastern Aravalli domain, western India. The Godhra granite have emplaced regionally along NW–SE trend, which splayed further SE-producing sporadic plutons (Mamtani et al. 2001; Mamtani and Greiling 2005). Emplacements of these plutons have locally deformed as well as generated contact metamorphism within Mesoproterozoic Champaner metasediments (Mamtani et al. 2001; Das et al. 2009; Limaye and Joshi 2016). The role of sporadic plutonic activity, however, induced structural complexity (Jambusaria and Merh 1967; Srikarni and Das 1996; Karanth and Das 2000). Doubly plunging Narukot dome, a part of Champaner Group forming southern extension of Aravallis in Gujarat, is one such feature that gives an opportunity to study the relationship of pluton and associated deformation. Deciphering subsurface morphology of pluton becomes vital.

Globally, the plutons are understood emplacing country rock with several geometric shapes, viz. circular, thick disk, sheet-like, hockey puck, flat-floored, wedge-shaped and many other discrete forms (McSween and Harvey 1997; Benn et al. 1998; Vigneresse et al. 1999) that in turn depend on the heterogeneity of magmatic activity, depth, and their degree of isolation as well as volume, strength and density difference between the plutonic melt and the country rocks (Bott 1955; Pitcher 1979; Vigneresse 1995; Benn et al. 1998; Stevenson et al. 2006; Cruden 2008). Several geophysical methods are deployed to study plutons, viz. gravity (Bott 1955; Vigneresse 1990; Singh et al. 2004; Rao et al. 2006; Cruden 2008; Singh et al. 2014), magnetic (Mamtani and Greiling 2005); aeromagnetic (Sahu 2012) magnetotelluric (Sastry et al. 2008); deep resistivity soundings (Singh et al. 2008); and deep seismic methods (Kaila et al. 1981; Dixit et al. 2010).

We apply a cost-effective microtremor technique to map subsurface pluton covering a large area at a prerequisite terrain-specific resolution from 250 m to 1 km interval. The assessment was quicker than the conventional indirect methods. The microtremor method has been used successfully to map subsurface rheological boundaries based on strong acoustic impedance along contrasting density at sediment/rock interphases at shallow depths and across fault zones (Kanai 1957; Yamanaka et al. 1994; Ibs-Vonseht and Wohlenberg 1999; Delgado et al. 2000a, b; Parolai et al. 2002; Garcia-Jerez et al. 2006; Guéguen et al. 2006; Zhao et al. 2007; Dinesh et al. 2010; Rošer and Gosar 2010; Sukumaran et al. 2011; Paudyal et al. 2013).

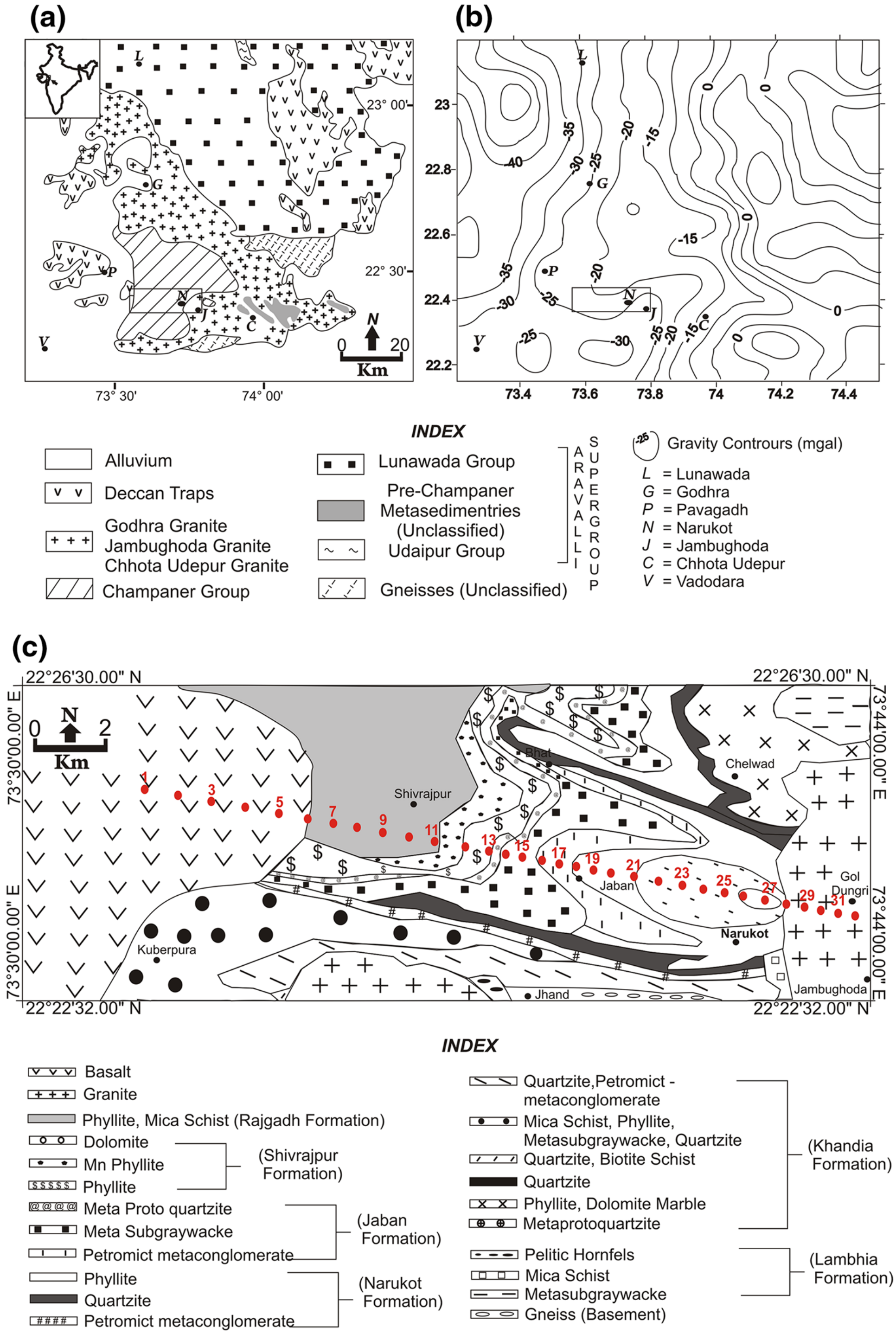
The present maiden attempt is to record a shallow seismic profile along doubly plunging Narukot dome and its western extension incorporating both microtremor method and field evidences. This enabled us (1) to delineate morphology of an independent granite pluton underneath the Narukot dome, (2) to determine the thickness of the Mn-bearing rocks of the Champaner Group, and (3) to infer implication towards syntectonic deformation of the Champaner Group.

## Geology and structures

The vast area E and SE of Narukot dome has a rolling topography with isolated highs that exposes Jambughoda Granite (1050 ± 50 Ma: Sm–Nd method, Shivkumar et al. 1993); Chhota Udepur Granite (1168 ± 30 Ma: Rb–Sr method, Srimal and Das 1998) and Godhra Granite (950 Ma, Rb–Sr method assuming an initial Sr ratio of 0.700, Crawford 1975; Rb–Sr method 955 ± 20 Ma, Gopalan et al. 1979; Rb–Sr method 938.8 ± 20 Ma, Srimal and Das 1998; Rb–Sr method 965 ± 40 Ma, Goyal et al. 2001) (Fig. 1a). Negative Bouguer gravity anomaly (−40 to −20 mgal) substantiates granites in the region (Fig. 1b; Sandwell et al. 2014). However, the structure and tectonic regime under which the granite emplaced remain indeterminate. The sporadic granite pluton under present study emplaces within Champaner metasediments comprising intercalated sequence of quartzites and phyllites (Narukot Formation) exposed in the eastern portion of the dome. This is followed by polymict conglomerate with lithicwacke (Jaban Formation) and Mn-bearing phyllites and quartzites (Shivrajpur Formation) in the central part, whereas thin phyllite–quartzite bands with dolomitic limestone (Rajgarh Formation) characterize the western extension (Fig. 1c; Table 1; Gupta et al. 1992, 1997). These sequences are regionally metamorphosed up to greenschist facies (Jambusaria and Merh 1967) and preserve relic primary sedimentary structures (Srikarni and Das 1996). Further, isolated development of hornfelses and skarn zones are observed close to the granitic body (Das et al. 2009). The extreme WNW portion of the Narukot profile under present study exposes Mesozoic sedimentaries and the Deccan basalts.

The deformation pattern of southern Aravalli domain comprising Lunawada and Champaner Group are not comparable to the main Aravalli domain. The main Aravalli domain shows two deformation phases ($AD_1$ and $AD_2$). $AD_1$ exhibits W trending rootless reclined, inclined, and rarely upright isoclinal folds. On the other hand, $AD_2$ are coaxial isoclinal folds with widely dispersed axial planes (Naha et al. 1966, 1969). Further south, the Lunawada Group displays $AD_3$ deformation comprising $LF_1$ and $LF_2$ coaxial folds (L: Lunawada) with NE-trending axial planes. $LF_3$ folds are open with

**Fig. 1** **a** Regional geological map showing extension of Aravalli Supergroup in Gujarat (after Mamtani et al. 2001). NW-trending batholith (Godhra Granite) constitutes the most conspicuous feature that demarcates the Lunawada Group at ENE and the Champaner Group at WSW. **b** Regional Bouguer gravity map showing extension of Aravalli Supergroup in Gujarat (Sandwell et al. 2014). **c** Geological map of study area (modified after Gupta et al. 1997). Oval structure along the E margin represents the Narukot dome with N95° axial trace. Dotted line across the dome and further W shows location of stations (1–32) for microtremor measurements




E- and NW-trending axial planes (Mamtani et al. 2001). Additionally, the Champaner Group demonstrates $AD_4$ deformation developing upright folds with E-trending axial traces ($CF_1$) followed by open upright cross folds with N–S axial traces ($CF_2$) emerging as large domal structures in Narukot and Poyali areas (Jambusaria and Merh 1967; Gopinath et al. 1977; Srikarni and Das 1996; Gupta et al. 1997; Karanth and Das 2000).

The domal character at Narukot is well preserved by quartzites that skirt the dome (Fig. 2a, b). Quartzite rimming N, E and S portion of dome shows discordant relation, steep dip, steep/vertical foliation and strong annealing. On the other hand, quartzites and phyllites in core region and towards the western margin show concordant relations, gentle westerly dip and regional metamorphism. Phyllites exposed adjacent to Narukot dome preserve S–C

**Table 1** Lithostratigraphy of southern Aravalli, Gujarat, W India after Gupta et al. (1992)

| Supergroup | Group | Formation |
|---|---|---|
| Post Delhi Igneous Intrusive | Idar Granite (Malani Igneous suite) | |
| | Erinpura Granite | |
| | Godhra Granite | |
| | Sendra–Ambaji Granite | |
| Delhi | Sirohi | |
| | Kumbhalgarh | |
| | Gogunda | |
| | Phulad Ophiolites | |
| Aravalli | Champaner | Rajgarh |
| | | Shivrajpur |
| | | Jaban |
| | | Narukot |
| | | Khandia |
| | | Lambia |
| | Lunawada | Kadana |
| | | Bhukia |
| | | Chandanwara |
| | | Bhawanpura |
| | | Wagidora |
| | | Kalinjara |

fabric (Passchier and Trouw 2005; Mukherjee 2011a, 2012, 2013a, b, 2014, 2015; Mukherjee and Kovi 2010a,b). Fieldwork did not reveal any visual effect of shear heating (Mukherjee and Mulchrone 2013; Mulchrone and Mukherjee 2015, 2016) The S- and C-planes meet at ~24°. The dip direction of both S–C fabrics is parallel to the plunge of open folds that characterizes western portion of the Narukot dome (Fig. 2c–e). Stereonet of lower hemisphere equal area projection containing $n = 67$ foliations have been plotted. Beta intersection diagram represents superimposition of N–S axial plane over the E–W trends. Beta-1 and Beta-2 are respective fold axes of $CF_1$ and $CF_2$ producing dome and basin geometry (Fig. 2f).

## Microtremor studies

Studies reveal that microtremors are activated by ambient noise that encapsulates the fundamental resonant frequency of near surface sediment horizons (Ohta et al. 1978; Celebi et al. 1987; Lermo et al. 1988; Nakamura 1989; Field et al. 1990; Hough et al. 1991; Yamanaka et al. 1994; Konno and Ohmachi 1998; Ibs-Vonseht and Wohlenberg 1999; Delgado et al. 2000a, b; Aki and Richards 2002). These resonating frequencies derived from microtremors strongly correlate with the velocity of seismic wave as well as the sediment thickness (Ibs-Vonseht and Wohlenberg 1999; Parolai et al. 2002). To characterize amplification of seismic wave for a given site, Nogoshi and Igarashi (1971) proposed a technique to normalize the source effect by taking the ratio of the horizontal (NS + EW component) and vertical component (H/V) of the noise spectrum. Nakamura (1989) further popularized the method and its applications. The merits and demerits of this method are discussed by several workers and has been used extensively as a low cost tool for site characterization in estimating the resonant frequency and thickness of sedimentary layers, viz. Field and Jacob (1993), Parolai and Galiana-Merino (2006), Bonnefoy-Claudet et al. (2006), Garcia-Jerez et al. (2006), Zhao et al. (2007), Nakamura (2008), Bard (2008), Pilz et al. (2009), Lunedei and Albarello (2010), and Sánchez-Sesma et al. (2011).

We deployed a Lennartz seismometer (5 s period) and a City Shark-II data acquisition system to acquire ambient noise in forms of three components, viz. NS, EW, and vertical directions. The recording was carried out for 40 min at the rate of 100 samples/s per site (Sukumaran et al. 2011, fig. 3). All the 32 geophysical stations (Fig. 1c) arrayed for measurement run almost parallel to the axial trace (N95°) of the Narukot Dome (Fig. 1c). The station interval was decided considering topography along the profile line. The region with rolling topography from station 1–13 (Fig. 1c) was surveyed at 1 km interval, whereas the rugged terrain, stations 13–32 (Fig. 1c), was surveyed at 500 m interval.

The ratio between the Fourier amplitude spectra of the horizontal to the vertical (H/V) components of persisting Rayleigh waves were calculated from the ambient noise vibrations acquired from 32 stations using the GEOPSY (SESAME European Project 2004). The H/V spectral ratios were plotted between 0.2 and 25 Hz encompassing the complete range of resonating frequencies recorded within the study area (Fig. 3). These H/V ratios were further processed individually to identify statistically significant spectral peaks using custom-written Matlab code. The statistically significant peaks were taken to be those peaks that were at least one standard deviation greater than the baseline activity. These peaks then correspond to significant fundamental resonating frequencies for each station. The significant fundamental resonating frequencies $f_0$, $f_1$ and $f_2$ were singled out for individual stations quantifying their amplitudes (Fig. 3; Table 2). Figure 3 illustrates a series of H/V spectral frequency plots recorded from the study area. Station 22, 30 and 31 show the peaks at fundamental frequency ($f_0$). Station 2, 3 and 4 show dual frequency ($f_0$, and $f_1$) with representing the boundary at both deeper and shallower levels. Station 15 and 29 too display dual frequency ($f_0$, and $f_1$) but at different frequencies that correspond to the boundary at moderate to shallower depth level. However, station 32

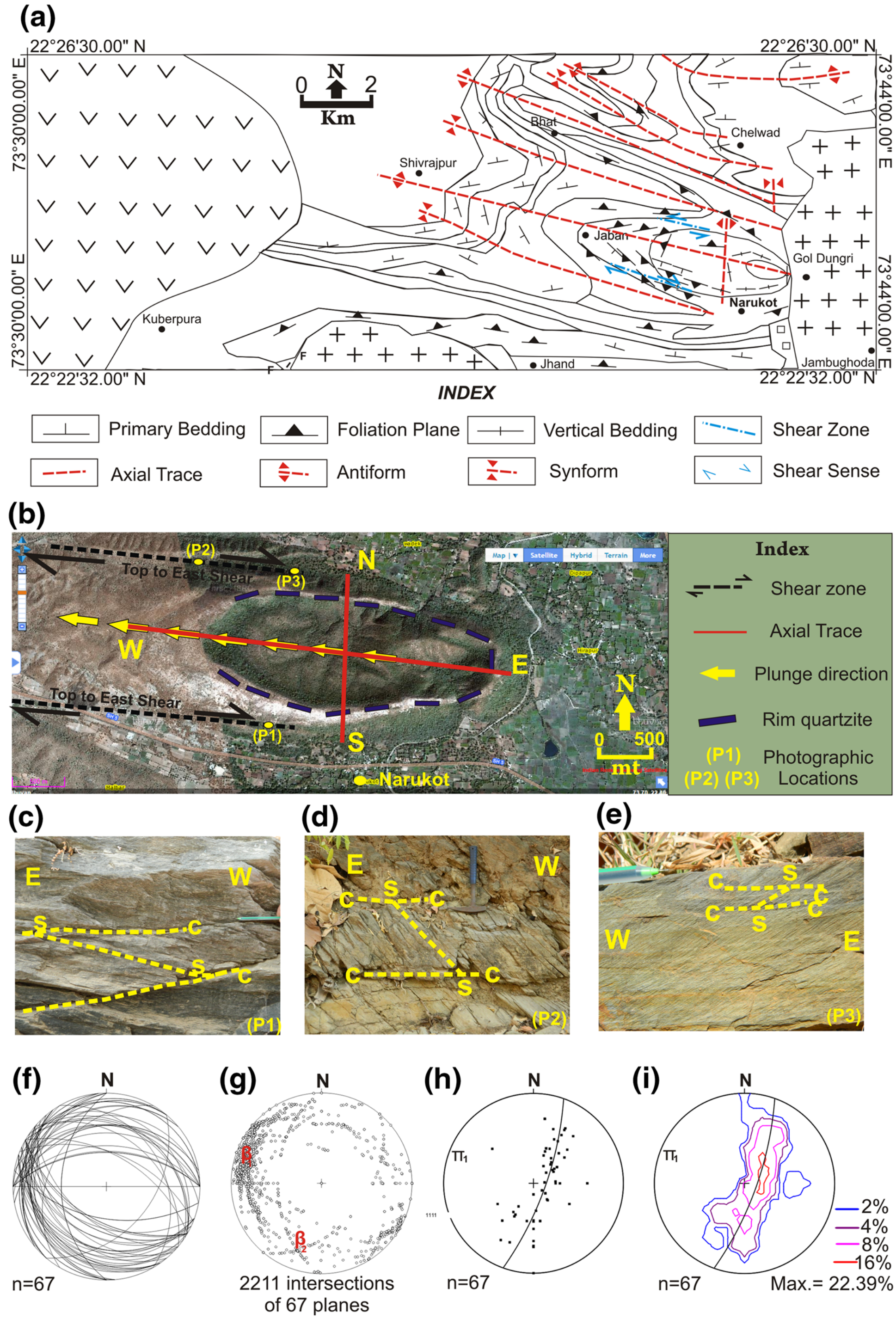



**Fig. 2** **a** Structural map of the study area (modified after Gupta et al. 1997). **b** Geo-eye image of Narukot Dome. N–S axial trace overlay over WNW–ESE trend; discontinuous lines: shear in the region; P1, P2 and P3: locations for field photographs. **c–e** Top-to-E ductile shear along vertical section. *S* schistosity fabric dipping steeper than the C-plane. **f** Foliation surfaces as great circles ($n = 67$, $S_0$, $S_1$). **g** Beta intersection diagram representing superimposition of N–S axial plane over E–W (2211 intersections of 67 planes). Beta 1 and Beta 2 are the respective fold axes of $CF_1$ and $CF_2$ producing dome and basin geometry. **h** Pie diagram ($n = 67$, $S_0$ and $S_1$) showing similar fold axes of $CF_1$ (i.e., N275°). **i** Contoured pie diagram; 2, 4, 8 and 16% contours per 1% area

represent three frequencies ($f_0$, $f_1$, $f_2$) incorporating three boundaries at shallow, moderate and deeper levels.

The thickness ($h$) of soil/sediment layer over the bedrock can be related theoretically with the fundamental resonant frequency ($f_r$) of H/V spectral ratio (Ibs-Vonseht and Wohlenberg 1999)

$$h = af_r^b, \quad (1)$$

where $a$ and $b$ are obtained by nonlinear regression between the thickness and the fundamental resonant frequency. For a given fundamental resonant frequency, if the velocity of seismic waves ($V_s$) for a given interphase is known, the depth of the interphases is given by Parolai et al. (2002):

$$h = \frac{V_s}{4f_r}. \quad (2)$$

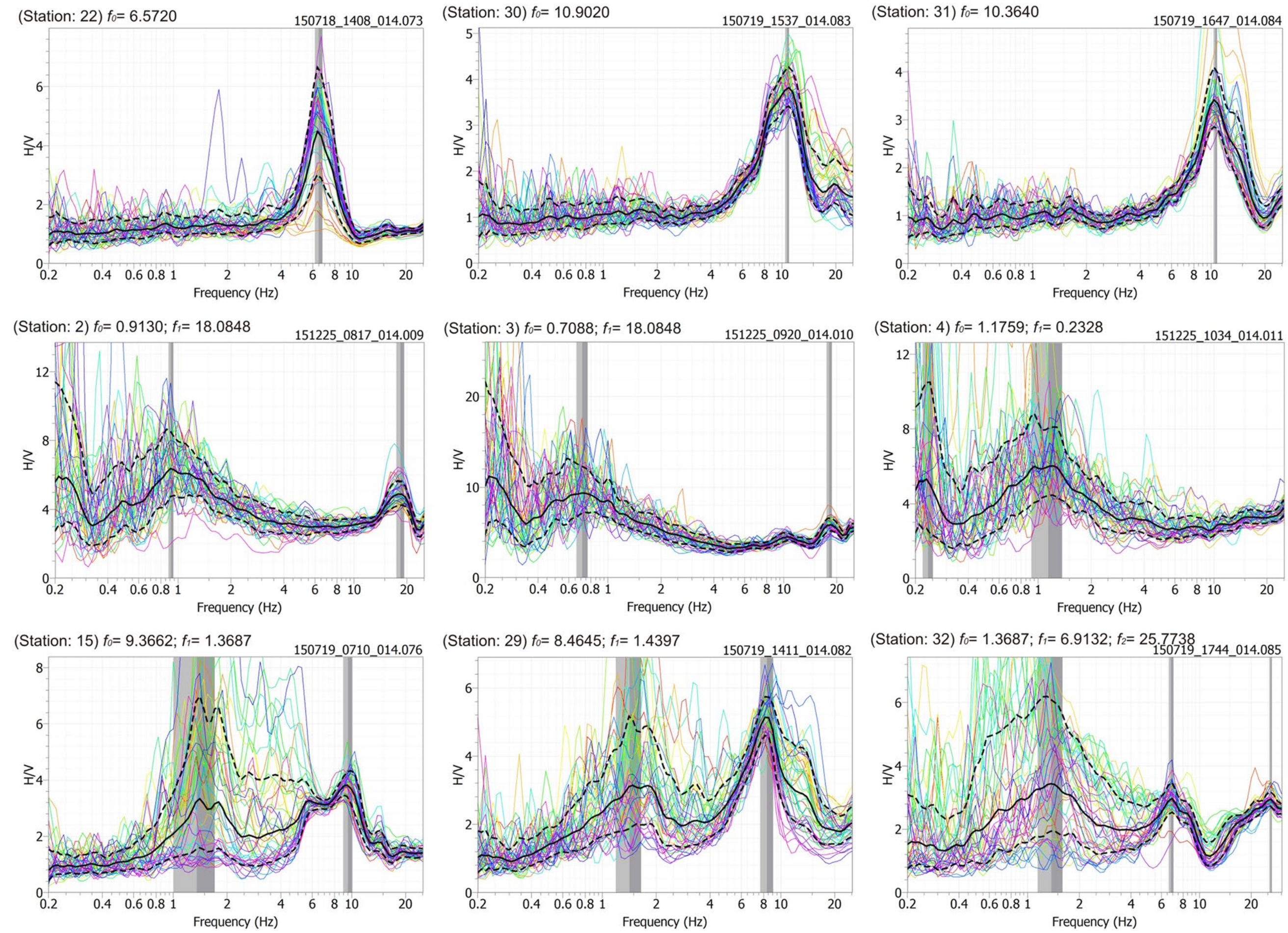



**Fig. 3** H/V spectral frequency plot recorded for the representative stations from the study area. Station 22, 30 and 31 show the peaks at fundamental frequency ($f_0$); station 2, 3 and 4 show dual frequency ($f_0$, and $f_1$) with representing the interphases at both deeper and shallower levels; station 15 and 29 also show dual frequency ($f_0$, and $f_1$) but at different frequencies that correspond to the interphases at moderate to shallower depth level. However, station 32 represent three frequencies ($f_0$, $f_1$, $f_2$) incorporating three interphases at shallow, moderate and deeper levels

On the other hand, if the depth of the interphase in known based on available core record, the velocity of seismic waves ($V_s$) can be determined using Eq. (2).

In the present study, we used a record of a private borehole 300 ft (91.4 m) closer to station 29, in Hirapur Village, east of Narukot dome. The records suggest 7-ft (2.13-m) thick soil unit, followed by 15-ft (4.57-m) thick white fine-grained sand (alteration product of in situ granite); and 278 ft (84.7 m) of massive granite. In the present case, we categorized both the soil unit and altered granite unit under the regolith. Using the observed depth of regolith–granite boundary (6.70 m), we computed $V_s$ (227 m/s) for the regolith unit at station 29 using Eq. (2). The depth of regolith–granite boundary for stations 28, 30, 31 and 32 has been estimated using the above computed value of $V_s$. In addition, substituting the value of $V_s$ in Eq. 2,

$$h = (56.8)f_r^{-1}. \tag{3}$$

Equation (3) derived from the study area is comparable to the equation derived for a granitic terrain around Bangalore (state Karnataka, India) decoding interphase of soil–regolith from that of granites (Dinesh et al. 2010), viz.

$$h = (58.3 \pm 8.8)f_r^{-0.95\pm 0.1}. \tag{4}$$

In this context, we preferred the equation established by Dinesh et al. (2010) in this study to derive theoretical depths of interphases as they had established the relationship using a larger number of observed borehole logs.

Further, grouping fundamental resonating frequency, geology and structural data from the study area, we identify two distinct rheological boundaries, viz. 0.2219–10.364 Hz that is inferred to record boundary between Champaner metasediment and granites (C–Gr boundary) and 10.902–27.1119 Hz that differentiates phyllites from quartzites (P–Qr boundary) (Figs. 4, 5). The other boundaries identified along the W margin of the profile, viz. 0.7088–12.6896 Hz

**Table 2** Fundamental resonant frequency $f_0$, $f_1$ and $f_2$ for station 1–32 across Narukot Dome and in its western extension along a WNW profile

| Stations | $f_o$ | Depth in m (Eq. 3) | Depth in m (Eq. 4) | $f_1$ | Depth in m (Eq. 3) | Depth in m (Eq. 4) | $f_2$ | Depth in m (Eq. 3) | Depth in m (Eq. 4) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.2328 | 243.814 | 232.828 | 0.913 | 62.169 | 63.565 | | | |
| 2 | 0.913 | 62.169 | 63.565 | 18.0848 | 3.139 | 3.726 | | | |
| 3 | 0.7088 | 80.079 | 80.848 | 18.0848 | 3.139 | 3.726 | | | |
| 4 | 1.1759 | 48.269 | 49.982 | 0.2328 | 243.814 | 232.828 | | | |
| 5 | 0.2328 | 243.814 | 232.828 | | | | | | |
| 7 | 12.6896 | 4.473 | 5.217 | 1.3011 | 43.625 | 45.402 | | | |
| 8 | 1.3011 | 43.625 | 45.402 | 25.7738 | 2.202 | 2.661 | | | |
| 9 | 1.18284 | 47.986 | 49.704 | 12.3244 | 4.605 | 5.363 | | | |
| 10 | 0.7456 | 76.127 | 77.053 | 25.7738 | 2.202 | 2.661 | | | |
| 11 | 27.1119 | 2.094 | 2.536 | 1.1759 | 48.269 | 49.982 | | | |
| 12 | 12.6896 | 4.473 | 5.217 | | | | | | |
| 13 | 18.0848 | 3.139 | 3.726 | | | | | | |
| 14 | 10.902 | 5.206 | 6.026 | | | | | | |
| 15 | 9.3662 | 6.060 | 6.961 | 1.3687 | 41.470 | 43.269 | | | |
| 16 | 8.904 | 6.375 | 7.304 | 18.0848 | 3.139 | 3.726 | 1.2369 | 45.889 | 47.638 |
| 17 | 14.7704 | 3.843 | 4.516 | | | | | | |
| 18 | 1.8543 | 30.610 | 32.426 | 25.7738 | 2.202 | 2.661 | 4.3838 | 12.948 | 14.319 |
| 19 | 1.5145 | 37.478 | 39.302 | 20.0113 | 2.836 | 3.384 | | | |
| 20 | 10.364 | 5.477 | 6.323 | 1.6758 | 33.870 | 35.699 | | | |
| 21 | 27.1119 | 2.094 | 2.536 | 19.0237 | 2.984 | 3.551 | | | |
| 22 | 6.572 | 8.637 | 9.747 | | | | | | |
| 23 | 1.8543 | 30.610 | 32.426 | | | | | | |
| 24 | 1.4397 | 39.425 | 41.239 | | | | | | |
| 25 | 18.0848 | 3.139 | 3.726 | | | | | | |
| 26 | 18.0848 | 3.139 | 3.726 | | | | | | |
| 27 | 19.0237 | 2.984 | 3.551 | | | | | | |
| 28 | 5.3676 | 10.575 | 11.813 | | | | | | |
| 29 | 8.4645 | 6.706 | 7.664 | 1.4397 | 39.425 | 41.239 | | | |
| 30 | 10.902 | 5.206 | 6.026 | | | | | | |
| 31 | 10.364 | 5.477 | 6.323 | | | | | | |
| 32 | 1.3687 | 41.470 | 43.269 | 6.9132 | 8.210 | 9.289 | 25.7738 | 2.202 | 2.661 |

The depths of rheological boundaries are calculated using Eq. 3 ($h = 56.8\, f_r^{\ -1}$: derived from borehole data from station 29 whereas Eq. 4 ($h = 58.3 \pm 8.8 f_r^{\ -0.95 \pm 0.1}$; Dinesh et al. 2010)

frequencies distinguish the boundary between the Champaner metasediments and the Mesozoic sediments. On the other hand, at stations 2 and 3, 18.0848 Hz frequency distinguishes thin Deccan traps from Mesozoic sediments.

### Champaner–granite boundary

The Champaner–granite boundary (C–Gr boundary) occurs at a shallower depth towards E than at the W margin of the profile showing an arched-up geometry (Fig. 5). The granite pluton attains shallowest depth calculated from surface underneath station 20 (35.69 m) and station 23 (32.42 m) followed by a significant depth, or a 'low', beneath station 6 (243.64 m) and station 1 (232.82 m) towards W. C–Gr boundary follows a steep slope between stations 7 (45.40 m) and 6 (243.64 m). The low along profile between stations 1 and 6 marks an extension of the younger Champaner rocks exposed around stations 7 and 8 (Rajgarh Formation) and is confirmed based on aeromagnetic data (Sahu 2012).

### Phyllite–quartzite boundary

The phyllite–quartzite (P–Qr boundary) sequence of Champaner Group is well exposed in the western

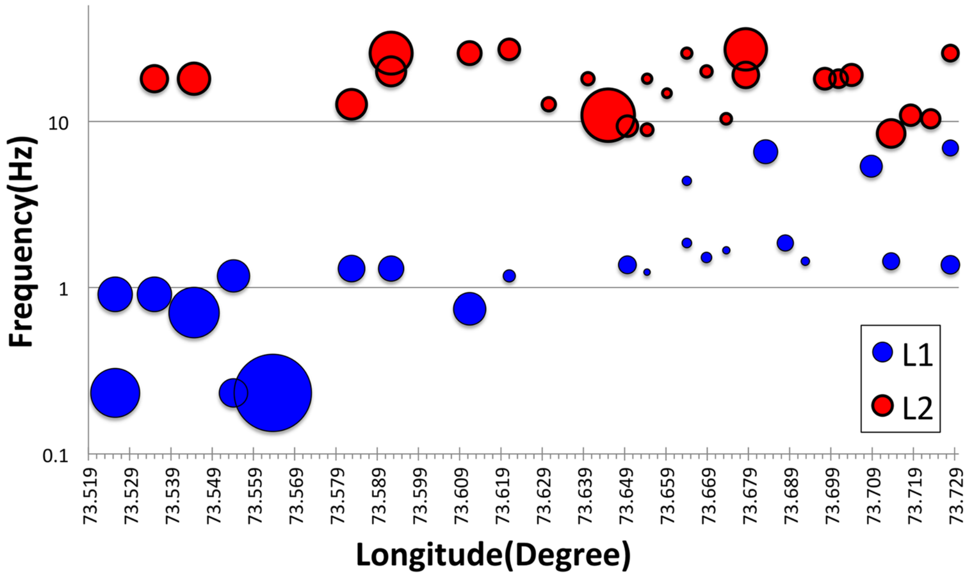



**Fig. 4** Fundamental resonant frequency of 1–32 stations along WNW trending profile. The diameter of bubbles captures amplitude of fundamental resonant frequency. The *blue color* represent frequency for C–Gr boundary ($L_1$) that ranges between 0.2219 and 10.364 Hz, whereas red color represents frequency for P–Qr boundary ($L_2$) that ranges between 10.902 and 27.1119 Hz

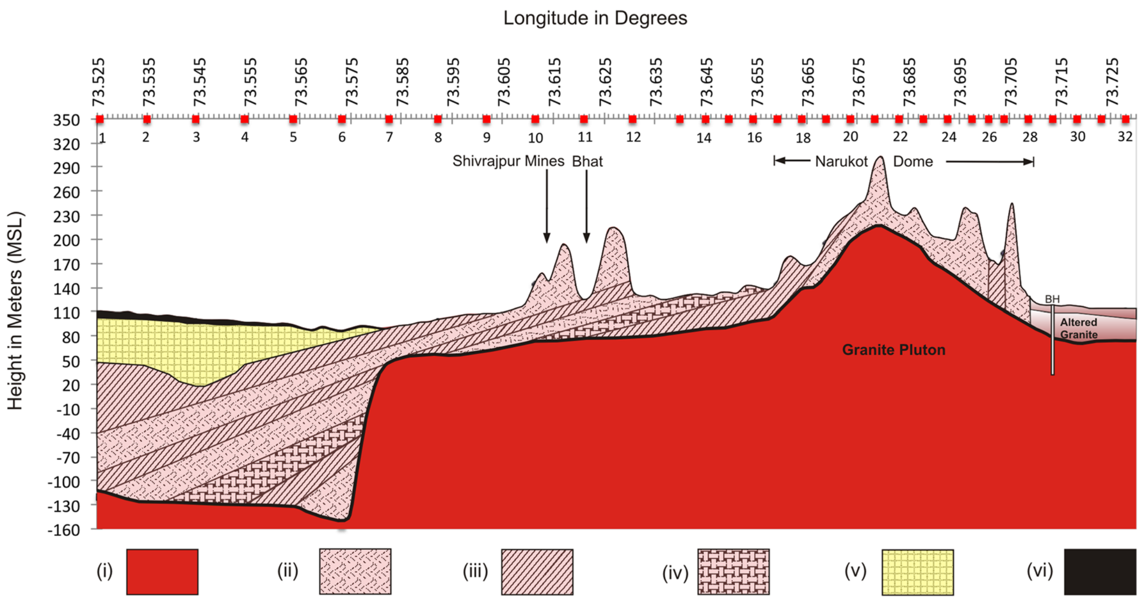



**Fig. 5** Layered model for the profile along Narukot dome and to its W. Subsurface interphases of C–Gr and P–Qr plotted with reference to the surface elevation. C–Gr boundary shows the granite pluton hump (from station 16 to 29) towards eastern part of the profile. The C–Gr interphase in W distinguishes a steep wall of the pluton (between stations 6 and 7) taking pluton further deeper to 243.64 m (station 6) and 232.82 m (station 1). The P–Qr boundary shows a steep plunge E of the granite pluton hump and 15° gentle plunge due W. The profile highlights subsurface extension of the Champaner Group further W overlain by Mesozoic sedimentaries and thin cover of Deccan basalt between stations 1 and 7. Numbers in the figure indicate (*i*) granite, (*ii*) quartzites, (*iii*) phyllites, (*iv*) conglomerate, (*v*) Mesozoic sedimentaries, and (*vi*) Deccan basalt

extension of Narukot dome. During the field studies, boundary of different lithology and their trends were recorded and mapped (Figs. 1, 2). Lithology and structural trends were plotted along the topographic profile, extrapolating their contact up to the C–Gr boundary (Fig. 5).

## Other rheological boundaries

In the western portion of the profile, the C–Gr boundary is ~240 m deep. The Rajgarh Formation in this part directly overlies granites deduced from aeromagnetic data (Sahu 2012). The boundary between the Rajgarh Formation and Mesozoic sediments is ~70 m deep. The boundary between the Mesozoic sediments and Deccan basalt is ~1–2 m deep (Fig. 5).

## Discussions

The microtremor study reveals Champaner–granite boundary as the most conspicuous rheological boundary that emphasizes the morphology of subsurface granite pluton (Fig. 5). The granitic pluton forms a hump between stations 29 and 16 followed by gentle westerly dip up to station 7. The profile between stations 6 and 7 highlights a steep wall of the granite pluton, with 230-m deep C–Gr boundary, thereafter follows a rolling topography till station 1. On the other hand, the Champaner metasediment terminates abruptly above granite plutons imparting a discordant relation. The sporadic granitic plutons emplaced in the terrain presumably uprooted the Champaner metasediments giving “rootless” characteristic especially at Narukot dome and to its West (Fig. 5). Further northeast of the Narukot dome, at Gol Dungari such rootless character can be deciphered (Limaye and Joshi 2016). The estimated vertical thickness of Champaner metasediments varies as: 30 m (station 20), 100 m (station 21) and goes to a maximum of 136 m (station 12) at the Shivrajpur Manganese Mine. In the W extension of Narukot dome, the estimated thickness of Rajgarh Formation is ~108 m followed by 70-m thick Mesozoic sediment capped by 1–1.5-m thick Deccan basalt.

To present the relation between the pluton and associated deformation, we draw a geological cross-section across Narukot Dome and its extension towards W, by applying standard method adopted in geological studies, extrapolating surface geology and structural trends up to regolith–granite rheological boundaries delineated by microtremor studies (Figs. 2, 5). The sporadic emplacement of plutonic bodies produced asymmetric plunge along the dome. The Champaner metasediments between stations 23 and 29, E of the pluton hump, are tightly folded and plunge steeply towards E (Fig. 2), whereas to the W of pluton hump (station 20) metasediments show open folds and plunge 15° due W (Fig. 2). However, the fold axis of both tight (towards E) and open folds (towards W) across the Narukot dome trends N95° signifying the same deformation phase (Fig. 2). The accompanied deformation in form of open folds with N and NW trends has further resulted into dome and basin geometry. A more detail mechanism of doming (such as Mukherjee 2011b; Mukherjee et al. 2010; Mukherjee and Mulchrone 2012) remains a subject of future research. Finally, pluton morphology, selective metamorphism and related deformations favor syntectonic granite emplacement. Similar observations have been made in the Lunawada region—further NE of the study area (Mamtani et al. 2001).

## Conclusions

(a) Microtremor method is a handy tool for geoscientists to infer morphology of subsurface plutons underneath meta-sedimentary sequence.
(b) Microtremor method would update the results along with field records to estimate thickness and to further project subsurface attitudes of the country rock.
(c) Country rock and pluton boundary, contact metamorphism and associated deformation connote syntectonic pluton emplacement.

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# Sequential Development of Microstructures in Quartzites of Champaner Group, Gujarat

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**Abstract**

The meta-sedimentary rocks belonging to Mesoproterozoic Champaner Group are exposed in the eastern extremity of Gujarat State, India. These rocks are characterised by argillaceous, chemogenic and organogenic compositions and surrounded by younger Godhra granite from three sides. The granitic intrusion resulted in the development of microstructures in quartzites particularly in the western and central region of the Champaner Group. The microstructures formed in quartzite include bulging recrystallisation (BLG), sub-grain rotation recrystallisation (SGR) and grain boundary migration recrystallisation (GBM). The grain boundary area reduction (GBAR) process is observed towards the eastern margin of Champaner Group, near granite contact. In spite of grain boundary area reduction, the quartz grains in quartzite replicate dislocations in the form of undulose extinction. This indicates that during microstructure generation the temperature was extremely high. However, prevailing high strain rate within grains during microstructure generation decreased the internal free energy and removal of dislocation from the mineral. Under microscope, quartzites reveal granoblastic, polygonal, mosaic or foam micro-textures size. The inequigranular quartz grain boundaries ranges from seriate to straight depending on its proximity to granitic intrusion. The quartz grains are associated with minor mica minerals like muscovite and biotite. Presence of occasional tourmaline in quartzites, in close proximity to granitic intrusion, indicates effect of boron metasomatism.

**Keywords:** Microstructures, Quartzite, Champaner Group, Godhra granite, Gujarat.

## Introduction

The Southern Aravalli Fold Belt is characterised by polyphase deformational history. It is the major orogenic belt of north western India, which occupies southern parts of Rajasthan and north east and eastern parts of Gujarat. The rocks of this fold belt include thick sequence of folded meta-sediments of Lunavada and Champaner Groups, which forms the upper horizons of Aravalli Supergroup.

The Mesoproterozoic Champaner Group is well developed in eastern Gujarat covering an area of 1400km$^2$ in Panchmahal and Vadodara districts between Latitude 22º15′:22º28′N and Longitude 73º30′:73º51′E (Fig.1) (Gopinath *et al*., 1977; Srikarni and Das, 1996). Lithologically, the area consists of thick assemblages of metamorphosed and complexly folded clastic sediments along with minor chemogenic and organogenic assemblages. The meta-sediments of Champaner Group form rectangular outline that were intruded by younger Godhra granites towards northern, southern and eastern margins and enveloped by extrusive Deccan Trap volcanics and infra-trappeans towards the west (Fig. 1). On the basis of homogeneity in rock types and occurrence of intra-formational conglomerate, the Champaner Group is divided into six formations *viz*. Lambia, Khandia, Narukot, Jaban, Shivrajpur and Rajgad (Gupta *et al*., 1997). These meta-sedimentary sequences of Champaner Group contain dominant quartzite in each formation.

Structurally, the Champaner Group exhibits two phases of folding *i.e*. D1 and D2. Due to this the entire sequence was folded to form an anticlinorium with westerly plunging antiforms and synforms. The first phase of deformation is dominant throughout the Group and characterised by E-W trending axial trace, whereas second phase of deformation resulted in N-S trending axial trace (Jambusaria and Merh, 1967). The effect of second phase decreases from eastern to western direction in the form of minor D2 kink folds. Both these phases are accompanied by synchronous emplacement of younger Godhra granite. The coarse grained Godhra granite is often porphyritic with phenocrysts of pink and grey feldspars. This granite has been dated at 955 ± 20Ma by Rb/Sr

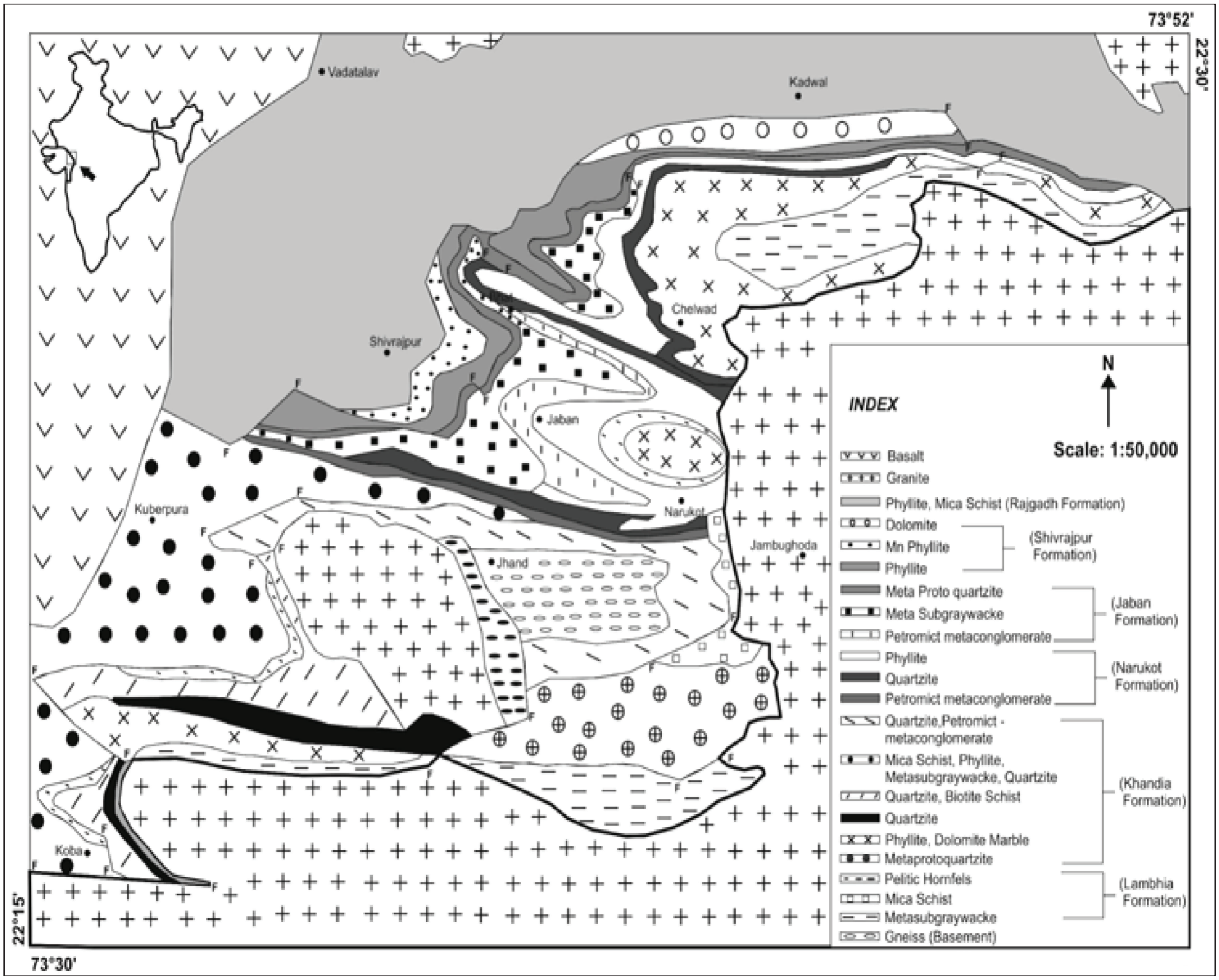


**Fig.1.** Geological map of Champaner Group (*modified after* Gupta *et al.,* 1997).

method (Gopalan *et al*., 1979). The quartzites of Champaner Group constitute intercalated sequence with phyllite making ridges that were deformed by D1 phase causing tight isoclinal folds, while phyllite occupy flat terrain.

The present investigation has been carried out on quartzites of Champaner Group, which are ubiquitous in each formation. The quartzites of the study area are hard, massive, compact and whitish to dark grey in colour. These are highly jointed and have variable grain size at different locations. In order to study such physical parameters grab sampling method has been adopted and samples located near as well as away from the granitic intrusion were collected. The microstructures observed in the quartzites of Champaner Group were used to decipher the micro-scale deformation mechanism and thermal characterisation of plutonic activity imparted by Godhra granite over quartzites in the study area. Thermal effect of Godhra granite and resulting stress conditions reflect variation in microstructures due to variation in its proximity to granitic intrusion.

## Microstructures in Quartzites

The petrographic study of quartzite under microscope reveals granoblastic polygonal, mosaic or foam microtexture (Vernon, 1976). The boundaries of inequigranular quartz grain ranges from seriate in distant to straight in proximity of Godhra granitic intrusion, respectively. These grains are associated with minor mica minerals like muscovite and biotite. The presence of occasional tourmaline in quartzites, in close proximity to granitic intrusion, indicates effect of boron metasomatism.

### *Bulging Recrystallisation (BLG)*

Quartzites found in and around Bamankuwa, Dolimaar and towards its south are characterised by bulging recrystallisation or low temperature grain boundary migration. Under microscope, the microstructures fall in regime 1 of (Hirth and Tullis, 1992). It can be seen that grain boundary of

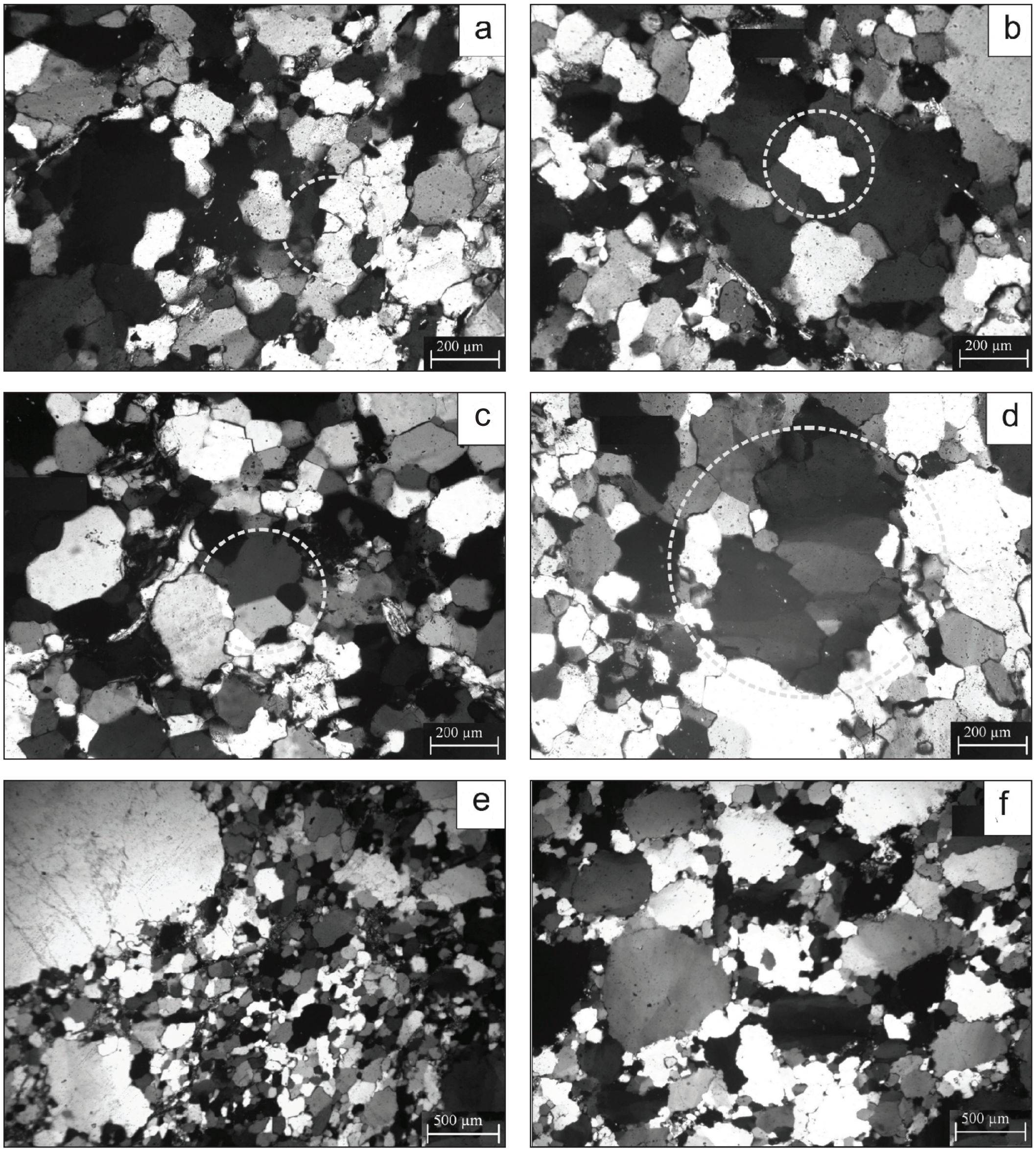


**Fig.2.** Photomicrographs of quartzites (4x Cross Nicols) showing effect of a) Bulging recrystallisation; b) Subgrain rotation recrystallisation; c) Grain boundary migration recrystallisation and leftover grains; d) Grain boundary area reduction causing triple junction along with undulose extinction and inequigranular polygonal shape; e) Inequigranular interlobate grain boundary; f) Seriate interlobate grain boundary.

one grain is bulging into other grain due to difference in dislocation density (Fig. 2a). This has formed along the boundaries of relict grains resulting in uneven grain shape and size. Such bulging is typically seen in strongly deformed quartz having temperature of formation less than 300°C (Wu and Groshong, 1991).

***Sub-grain Rotation Recrystallisation (SGR)***

The process of sub-grain rotation recrystallisation results into new grain formation that has high angle offset relation with the neighbouring grains. It is found in Keshavpura area and up to Malabar in south of the study area. This type of recrystallisation occurs due to adding up of dislocations to sub-grain boundaries. The photomicrograph shows disorientation of central grain with respect to surrounding host grains (Fig. 2b) and generally occurs at higher temperature than 300°C. A new grain is developed with transition from low angle to high angle in relation to relict old grains. This SGR microstructure corresponds to regime 2 of (Hirth and Tullis, 1992).

***Grain Boundary Migration Recrystallisation (GBM)***

At comparatively higher temperature condition than SGR, where grain boundaries become mobile and sweep material throughout the grain to remove dislocations called grain boundary migration (Fig. 2c). It is found largely near

Lobiya and Mota Raska villages. Due to GBM, all dislocations are found to be removed from quartz grains, resulting in inequigranular inter-lobate boundaries. The variability in grain size makes it difficult to distinguish between new and older grains. The left over grains are characteristic features of GBM and fall under regime 3 of (Hirth and Tullis, 1992). Due to this type of recrystallisation process the grains become strain free and show straight extinction (Passchier and Trouw, 2005).

### *Grain Boundary Area Reduction (GBAR)*

GBAR is a dominant phenomenon observed in regions of Narukot, Wadli, Wav and Rustampura. The quartz grains in these quartzites show reduction in free inter-granular space and decrease in total surface area along with increase in grain size. This grain growth is a result of annealing, wherein the small grains resorb to form coarser grains with straight boundaries. The quartz grains show undulose extinction and are largely polygonal in shape with the presence of triple junction between adjacent grains having 120° interfacial angle (Fig. 2d).

## Discussion and Conclusions

Microstructures enumerated above show distinct variation in parameters such as grain size, grain shape, free internal energy and extinction. Such distinct microstructural variability has been observed in quartzites from Bamankuwa in the west up to Narukot in the east of Champaner Group, in the form of sequential development of microstructure *viz*. BLG, SGR, GBM and GBAR. Western part reveals BLG, SGR and GBM mechanism with the presence of straight extinction, whereas the eastern part discloses GBAR as a dominant process due to high temperature condition along with undulose extinction.

In the extreme west of Champaner Group, where it is obliterated by the cover of Deccan traps, grain size is found to be fine having irregular grain shape with high free internal energy. BLG is the dominant process in this region. Prograding towards the central part of Champaner Group, the grains tend to increase and become moderate in size with inequigranular (Fig. 2e) to seriate inter-lobate (Fig. 2f) in shape. This gradual increase in grain size indicates reduction in free internal energy which is displayed in microstructures including SGR and GBM. The quartzites closer to Godhra granite in the northern, eastern and southern fringes represents maximum increase in grain size with inequigranular polygonal shape having straight boundaries and triple junctions. Such coarseness implies thermal maxima of plutonic intrusive mass along with low free internal energy causing GBAR mechanism. The quartz grains in quartzite, in vicinity of granite, show dislocation in the form of undulose extinction, which indicates that during microstructure generation the temperature was extremely high. However, prevailing high strain rate within grains during microstructure generation caused decrease in internal free energy and removal of dislocation. Conclusively, the post deformational sustained heat of Godhra granite emplacement at the end of orogeny and induced deformational stresses are the main factors for development of these microstructures.

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# EVIDENCE OF SYN-DEFORMATIONAL GRANITOID EMPLACEMENT WITHIN CHAMPANER GROUP, GUJARAT

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**Abstract:** Precambrian rocks of Champaner group located at the eastern extremity of Gujarat is characterised by covering from three sides, younger Godhra granitoid. This granitoid has been found to have intrusive relationship with the Champaner group of rocks. The variety of granitoid encountered within the study area is also referred as unclassified granites and gneisses by the earlier workers, due to the presence of foliations at some places. It has been found that there exists strong intermixing of these varieties with the country rocks which makes it difficult to differentiate between them. The main emphasis is given in present study to the structural evidences recorded in these granitoids with respect to Champaner group of rocks. By carrying out rigorous field studies it is seen that the granitoid display similar structural disposition that of Champaner, which suggest that the deformation was active till end phase of plutonic intrusion to shape itself in the identical fashion. On the contrary these granitoids were responsible to deform Champaner group of rocks, which was emplaced synchronously.

**Keywords: Champaner group, Godhra granitoid, deformation**

**Introduction:** Southernmost tip of Southern Aravalli Mountain Belt (SAMB) is located in the extreme eastern part of Gujarat. These rocks are of Champaner group having meso-proterozoic age and are covered from northern, eastern and southern sides by younger plutonic intrusive (i.e. Godhra granite), while there exists deccan trap formation in the west (Gupta et. al. 1992, 1995) **(Fig.1)**. On the basis of intraformational conglomerate the group is divided into six formations, viz. Lambia, Khandia, Narukot, Jaban, Shivrajpur and Rajgad, having total surface area of 1400 sq km (Gupta et. al. 1997). Structurally rocks of this region have undergone two phases of deformation, viz. $D_1$ and $D_2$. $D_1$ phase is dominant throughout the group and resulted in E-W trending folds while D2 phase of deformation has its feeble effects from east to west and are characterised by N-S trending folds (Jambusariya and Merh 1967, Gopinath et. al., 1977, Merh 1995). Due to its low deformed nature Champaner group has been a centre of debate with regards to its stratigraphic position. (Gupta et. al. 1980, 1992, 1995) consider it as the youngest group of the Aravalli Supergroup, and Roy (1988) has suggested that it is younger than the Delhi Supergroup. Apart from the nature of folds and intergroup stratigraphic order, Champaner group is very poorly studied region in SAMB. Though holding its economic importance in manganese as well as uranium mineralization an attempt to give overall structural evaluation deserves further investigation.

The granite present within and all three sides of Champaner group vary in terms of its appearance and play a dominant role in defining its architecture. The relationship of granite with the present group is of intrusive nature. However in precambrian tectonics, granitic intrusions which are associated with several deformation events are useful in constraining the age of deformation (Sychanthavong, 1990). The reason for applying granitoid term (Winter 2010) against granite is due to its complex origin encountered in the present study. The granite origin is always controversial but earlier results from different precambrian terrain suggest emplacement and crustal deformation may be interrelated and synchronous process (Solar et. al., 1998; Pressley and Brown, 1999). Aim of this paper is to document the field observations in granitoids supporting syndeformational event of Champaner group lying in the vicinity of Jhand and adjacent areas. Moreover, a correlation in terms of structural disposition is established by taking into account linear and planer features present within the study area. The paper also highlights microstructural evidences encountered within these granitoids.

**Geological setup:** The study area is characterised by various lithological entities such as Oligomict meta-conglomerate, quartzite, phyllite, pelitic-hornfels of Lambia formation and younger granitoid rock of foliated as well as non-foliated variety. The Oligomict meta-conglomerate encountered within the study area is the considered to be the basal conglomerate of Lambia formation. The pebble sized clasts are rounded to sub-rounded in nature, dominantly of quartz embedded in dark grey colour matrix **(Fig.2a)**. This meta-conglomerate horizon is in 'L' shaped manner, exposed 2.5 km south west of Jhambughoda and can be traced along road section from Mota-Raska towards Jhand. Overlying quartzite is massive fine grained dark grey in colour and display significant structural signatures in terms of folds and warping **(Fig.2b,c)**. Prominent kink bands are characteristics of fine grained phyllitic rock adjacent to the quartzitic horizon **(Fig.2d)**.

Due to the effect of Godhra granitoid there has been developed pelitic hornfels in contact aureole between Jhand and Sagva (Bhatt et. al. 2012). The rock is hard, massive dark green in colour and show prominent foliations. Similar hornfelsic rocks and magnesite bearing calc-silicates have been reported from Wadek and Chalvad region by (Das et. al. 2009, Sharma et. al. 2013). Appearance of granitoids within the study area varies at different places. There are in all two main varieties identified based on foliated and non-foliated nature. The foliated variety is whitish-grey in colour, coarse grain with the development of feeble gneissic structure on outcrop scale **(Fig.2e,f)**. Dominant mineral assemblage are quartz, K-feldspar with biotite segregation. Microstructurally, the quartz grains in foliated granitoids are extensively strained and show development of subgrains. Such straining indicate intracrystalline deformation and recovery (Passchier and Trouw 2005) during folding, representing active deformation till end phase of magma consolidation **(Fig.3a,b)**.

The non-foliated variety are of two types distinguish based on the colour and nature of grain size. The areas near Lambia village have non-foliated granitoid rock of pink colour with the effect of boron metasomatism resulting in the formation of tourmaline mineral **(Fig.3c)**. Another non-foliated whitish-grey variety ranges in grain size from fine to coarse.

Fine grained granitoid is commonly found to occur in association with the coarse grained granitoid; at places, the latter is seen to have an intrusive relationship with the former. Such features indicate coarse grain granitoid is evolved subsequent to the fine grained **(Fig.3d)**.

**Structural Setup:** Southern most part of Aravalli domain represented by Champaner group of rocks are characterised by atleast two phases of deformation **(Fig.4a)**. $D_1$ is present throughout the group displaying E-W trending folds while $D_2$ phase of deformation is represented in the form of N-S trending folds (Shah et. al. 1984), however derivatives of both the phases of deformation are present within the study area **(Fig.4b)**. The quartzitic ridges, east of Jhand have strike E-W with variable dip direction represent regional scale antiformal and synformal structure. Similar meso-scopic folds in quartzite are also observed in unlined canal section, north of Mota Raska village. The folds are tight in nature with westerly plunge of 15˚. The variety of foliated granitoid on a regional scale has been mapped, which display similar folded antiformal and synformal structure. The axial trace of these foliated antiformal folded outcroups can be trace along unlined canal section till west of Jhand and another axial trace of synformal structure can seen along north of Mota Raska till east of Lambia village. The overall morphology of these foliated granitoids is enveloped from three sides by quartzitic ridges forming an outlier. These structural features can be correlated with E-W deformation of Champaner group. Derivatives of second phase of deformation can be seen over quartzites and phyllites in the form of N-S warping and Kink bands respectively. However the effects of second phase of deformation have not been witnessed over foliated granitoids. In order to visualize the identical style of folding of foliated granitoids **(Fig.4c)** and quartzites **(Fig.4d),** respective planer features have been plotted which resulted in identical structural attributes calculated through it.

**Discussion:** The detail structural analysis of the study area reveals that D1 phase of deformation is dominantly seen to have E-W trending regional plunging tight folds in quartzites and ganitoids. Whereas D2 phase of deformation is represented by N-S trending warping and kink bands in quartzite and phyllite. By correlating the structural attributes of quartzites and granitoids, gives the idea of identical sense of folding. The granitoids of this region have been dated by Rb/Sr method which reflect the age (955± 20 my) (Gopalan et. al. 1979) and are the result of within plate collision activity (Goyal et. al. 1997) in which partial melting of lower crust was involved due to heat supplied by upper mantle giving rise to A-type granitoids . However still older granitoid intrusions of 1100 my from the Jhambughoda area have been reported by (Shivakumar et. al. 1993). On the basis of these variations in geochronology of granitoids, it postulates two different pulses in the present region. Such evidences can be substantiated in the field by studying granitoids which are devoid of N-S folding. The granitoid intrusion which was responsible to give rise D1 phase of deformation might be older than the pulse which gave later D2 deformation. Based on our results it is suggested that after the emplacement and consolidation, the granitoid has been synchronously co-folded along with the country rocks.

Similar synchronous emplacement has been recorded from Devghad Bariya region situated NE of Champaner group. These rocks represent Lunawada group and gets terminated in the vicinity of Devgadh Bariya where they come into contact with granitic and gneissic rocks; the latter are known to constitute the Godhra Granite and Gneiss (Srikarni et. al., 1992). Lithologically Lunawada group comprises meta-sedimentary rocks and are involved in at least three deformation events associated with regional metamorphism and exhumation (Mamtani, 1998; Mamtani et al., 1999a,b, 2000, 2001; Bakker and Mamtani, 2000). Based on the field as well as magnetic foliations from granite and gneisses of Devghad Bariya suggest similar trend coinciding with D3 deformation of Lunawada region (Mamtani et. al., 2005). In addition to that these granites accommodated deformation and strain during its evolutionary history. Identical to that of Champaner's, there exists a probability that these granitoids must have derived by melting of the gneiss and were emplaced synkinematically (Mamtani et. al., 2002).

## Conclusion

Based on the field as well as lab investigation it can be inferred that the quartzite and foliated granitoid show similar sense of folding, suggesting synchronous deformation along with the granitoid emplacement. Based on cross cutting field relationship it can be said that coarse grain non-foliated granitoid is evolved subsequent to the fine grained. The quartz grains in foliated granitoids exhibit strained nature, implying intracrystalline deformation active till synchronous emplacement.

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**Captions:**

Fig.1: Lithostratigraphic map of Southern Aravalli Mountain Belt, modified after Gupta et. al., 1992.

Fig.2: Field photograph showing: (a) Pebble sized clasts in oligomict meta-onglomerate. Loc. Mota Raska. (b) Tight fold in quartzite. Loc. Mota Raska. (c) N-S trending warps in quartzite. Loc. Mota Raska. (d) N-S trending kink bands in phyllite. Loc. Mota Raska. (e) Intermixed granitoid of foliated variety .Loc. Jhand. (f) Meso-scopic view of feeble gneissic structure in granitoid. Loc. Lambia.

Fig.3: (a) Photomicrograph of granite representing subgrain development in quartz grains. (b) Photo--micrograph of granite showing undulose extinction in quartz, implying intracrystalline deformation. © Field photograph of non-foliated granite showing presence of tourmaline mineral indicating boron metasomatism. (d) Field photograph showing discordant interrelationship of coarse grain and fine grain granite.

Fig.4: (a) Litho-stratigraphic map of Champaner group, modified after Gupta et. al., 1997. (b) Enlarged litho-stratigraphic map of the study area. (c) Streographic plot of foliated granitoid. (d) Streographic plot of quartzite.

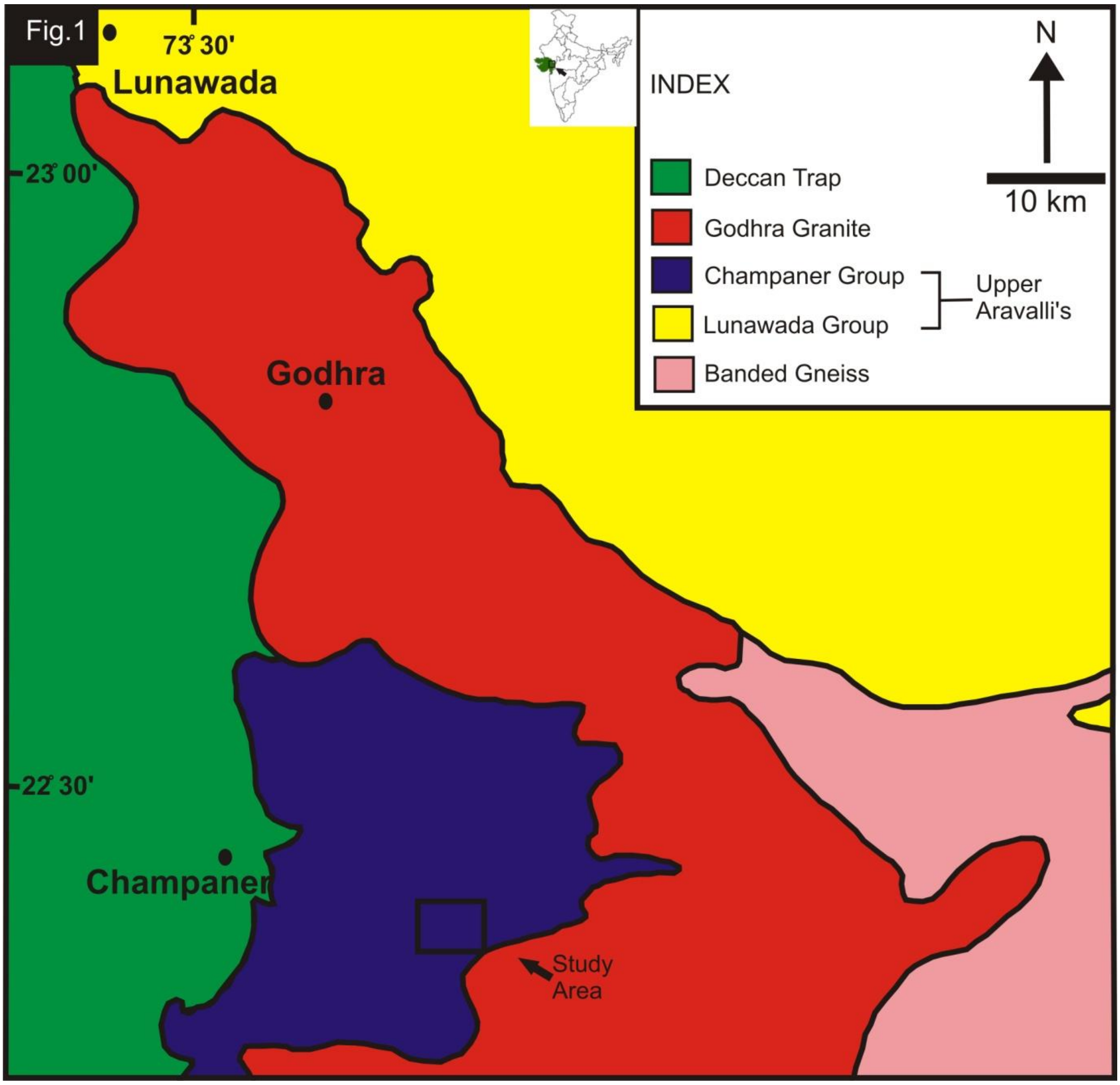
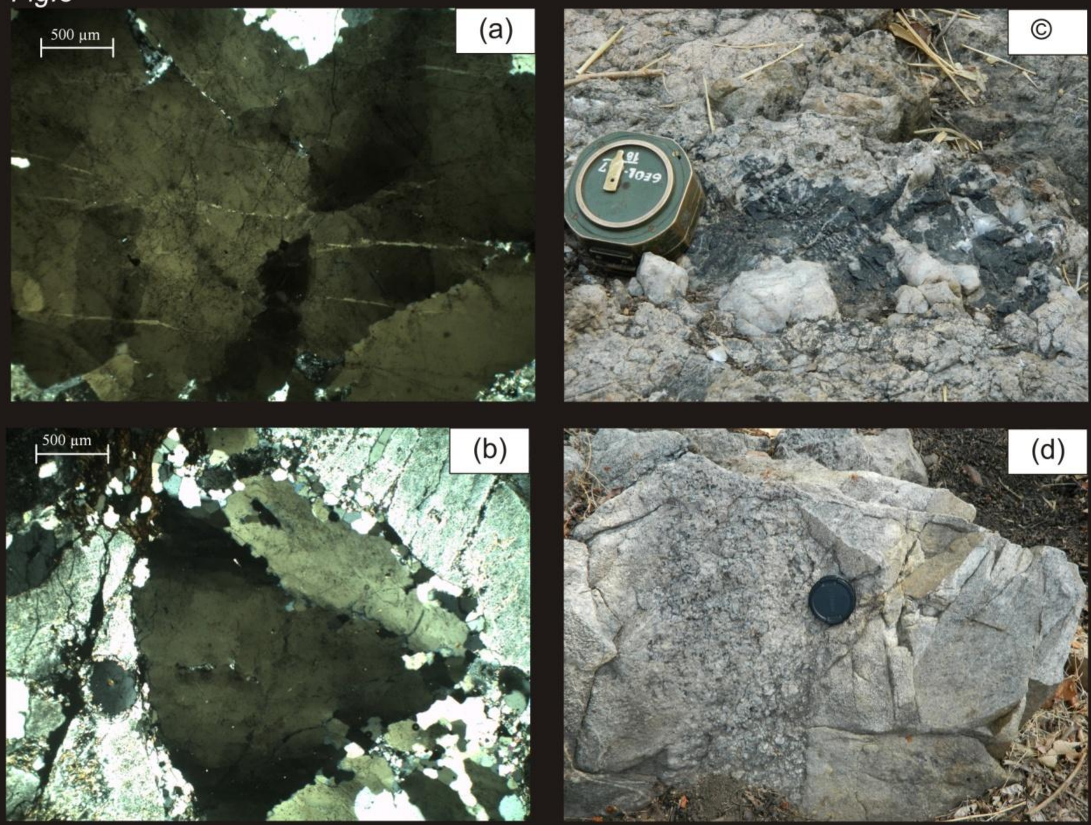


Fig.1
73° 30'
Lunawada
23° 00'
Godhra
22° 30'
Champaner
Study Area
INDEX
Deccan Trap
Godhra Granite
Champaner Group
Lunawada Group
Upper Aravalli's
Banded Gneiss
N
10 km

*Fig. 2*


Fig. 2: Field photograph showing: (a) Pebble sized clasts in oligomict meta-conglomerate. Loc. Mota Raska. (b) Tight fold in quartzite. Loc. Mota Raska. (c) N-S trending warps in quartzite. Loc. Mota Raska. (d) N-S trending kink bands in phyllite. Loc. Mota Raska.(e) Intermixed granitoid of foliated variety . Loc. Jhand. (f) Meso-scopic view of feeble gneissic structure in granitoid. Loc. Lambia.

*Fig.3*

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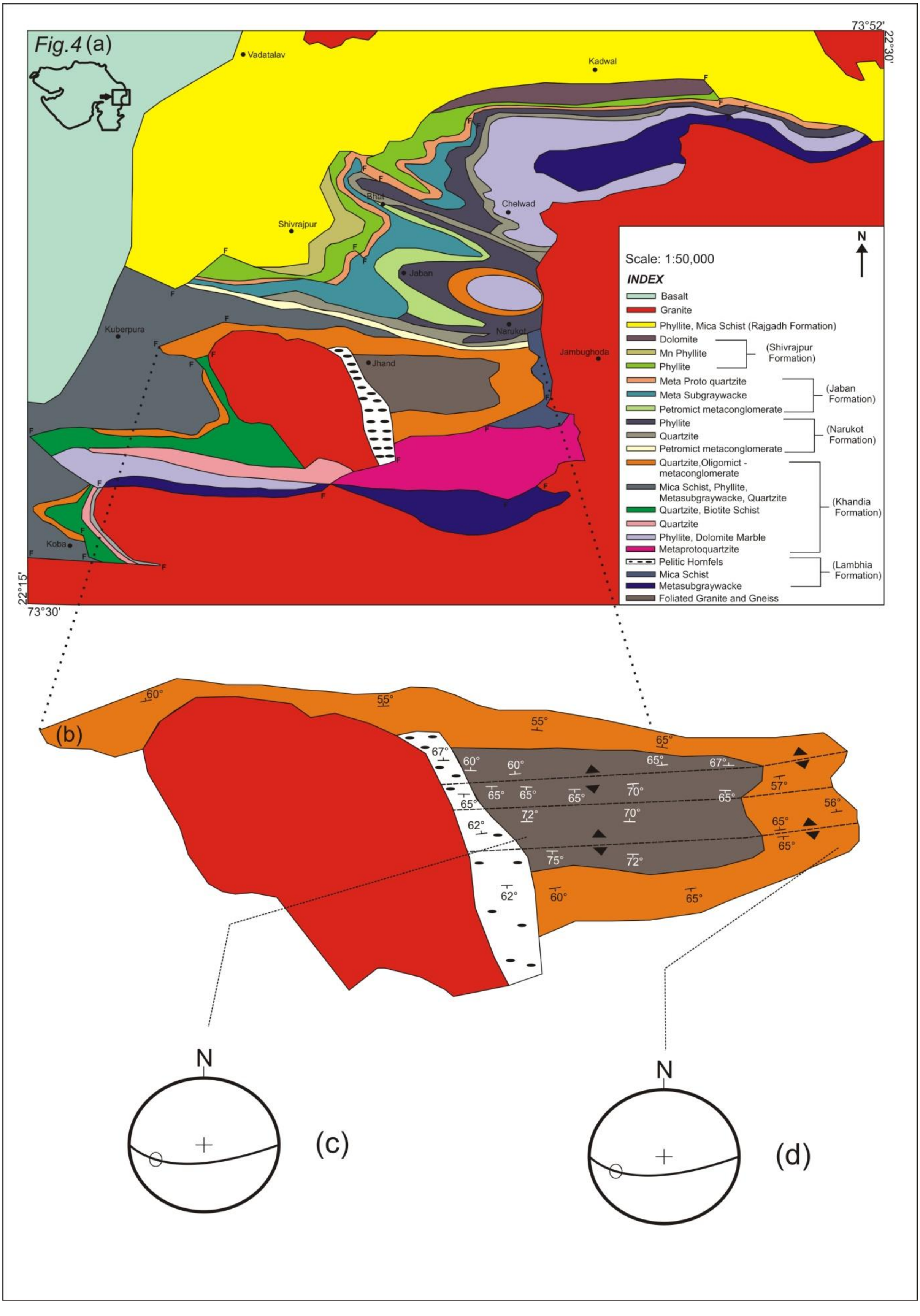

Fig.4 (a)
Vadatalav
Kadwal
Shivrajpur
Bhat
Chelwad
Jaban
Narukot
Kuberpura
Jhand
Jambughoda
Koba
73°52'
22°30'
22°15'
73°30'
Scale: 1:50,000
N
INDEX
Basalt
Granite
Phyllite, Mica Schist (Rajgadh Formation)
Dolomite
Mn Phyllite
Phyllite
(Shivrajpur Formation)
Meta Proto quartzite
Meta Subgraywacke
Petromict metaconglomerate
(Jaban Formation)
Phyllite
Quartzite
Petromict metaconglomerate
(Narukot Formation)
Quartzite,Oligomict - metaconglomerate
Mica Schist, Phyllite, Metasubgraywacke, Quartzite
Quartzite, Biotite Schist
Quartzite
Phyllite, Dolomite Marble
Metaprotoquartzite
(Khandia Formation)
Pelitic Hornfels
Mica Schist
Metasubgraywacke
(Lambhia Formation)
Foliated Granite and Gneiss
(b)
(c)
(d)
N