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Abstract

Trans-Aravalli terrane in the NW India is represented by Neoproterozoic volcano-sedimentary succession of Punagarh Basin that unconformably overlies deformed and metamorphosed basement rocks of Sojat Formation. The basement rocks were deformed into upright inclined folds with parallel to chevron geometry. The axial plane cleavages were developed showing variation in trend from NE-SW to ENE-WSW and this variation was due to late generation open folds. The folded rocks were superimposed by normal as well as strike faults which vary from planar to listric geometry. Due to block rotation roll over antiforms with complimentary synforms were developed. Erinpura granites and Malani Igneous Suite intruded Sojat Formation. Punagrh Group is subdivided into three Formations namely Bambholai Formation, Khamal Formation and Sowaniya Formation represented by quartzite, shale and bimodal volcanics. The lithological sequence suggests a deposition in a continental rift environment where volcanics were associated with shelf water facies. Normal as well as strike slip faults were developed in the sediments and are syn-kinematic to deposition. While the normal faults strike NE-SW direction the strike slip faults are in WNW-ESE direction. Small scale roll overs, drag folds and flanking structures are associated with normal faults while en-echelon arrays of quartz veins are associated with the strike slip faults. The paleostress tensor analysis of small scale faults suggests a NW-SE extension created normal faults while the strike slip faults were produced from a NNW-SSE compression.



Keywords (separated by '-'): Punagarh basin - Sojat formation - Normal and strike slip faults - Extensional setting

# Deformation and Tectonic History of Punagarh Basin in the Trans-Aravalli Terrane of North-Western India

**Anamika Bhardwaj and Tapas Kumar Biswal**



**Abstract** Trans-Aravalli terrane in the NW India is represented by Neoproterozoic volcano-sedimentary succession of Punagarh Basin that unconformably overlies deformed and metamorphosed basement rocks of Sojat Formation. The basement rocks were deformed into upright inclined folds with parallel to chevron geometry. The axial plane cleavages were developed showing variation in trend from NE-SW to ENE-WSW and this variation was due to late generation open folds. The folded rocks were superimposed by normal as well as strike faults which vary from planar to listric geometry. Due to block rotation roll over antiforms with complimentary synforms were developed. Erinpura granites and Malani Igneous Suite intruded Sojat Formation. Punagrh Group is subdivided into three Formations namely Bambholai Formation, Khamal Formation and Sowaniya Formation represented by quartzite, shale and bimodal volcanics. The lithological sequence suggests a deposition in a continental rift environment where volcanics were associated with shelf water facies. Normal as well as strike slip faults were developed in the sediments and are syn-kinematic to deposition. While the normal faults strike NE-SW direction the strike slip faults are in WNW-ESE direction. Small scale roll overs, drag folds and flanking structures are associated with normal faults while en-echelon arrays of quartz veins are associated with the strike slip faults. The paleostress tensor analysis of small scale faults suggests a NW-SE extension created normal faults while the strike slip faults were produced from a NNW-SSE compression. AQ1

**Keywords** Punagarh basin · Sojat formation · Normal and strike slip faults
Extensional setting

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## Introduction

The North-Western part of Indian shield has preserved a Precambrian geologic history in the form of Aravalli Mountain Ranges and adjoining areas. It has a record of 3500 million years old geological processes and tectonic events. On either side of the Aravalli Mobile belt, there are very large and thick intra-cratonic sedimentary successions of Vindhyan basin in the east and Marwar basin in the west. They are commonly known as the Purana basins having Meso-Neoproterozoic age. Along with these basins the Trans-Aravalli terrain which is a tectono-thermally stable low relief area lying west of Aravalli Mountain Ranges has preserved several isolated volcano-sedimentary basins such as Sirohi basin, Punagarh basin and Sindreth basin, which have different lithopackages and deformation history. The area is mostly covered with tertiary sediments leading to scanty rock outcrops. These basins have recorded late phases of Neoproterozoic crustal evolution of NW Indian shield. Tectonically these basins are different from Purana basins and not much attention has been paid to the detailed structural analysis and understanding deformational history of these basins. Punagarh basin is one such basin where we attempted to deduce the deformational history of the basin in order to understand its significance for tectonic models of Late Precambrian continental evolution.

## Regional Geology

The Aravalli-Delhi Mobile belt of the northwestern India depicts a juxtaposition of several terranes along NE-SW trending shear zones which appear as lineaments on the map (Fig. 1 inset). The terranes are namely, Hindoli-Jahajpur Terrane, Mangalwar and Sandmata Terrane, Aravalli Terrane, North Delhi Terrane, South Delhi Terrane and Sirohi Terrane (Singh et al. 2010). The individual Terranes are characterized by distinct sedimentation, deformation, metamorphism and magmatic history. Untala granites, Mewar gneiss, Annasagar gneisses and migmatitic gneisses of Mangalwar and Sandmata Terrane constitute the Archean rocks of the Mobile Belt (ca 3500–2700 Ma, Macdougall et al. 1983; Gopalan et al. 1990; Wiedenbeck and Goswami 1994; Tobisch et al. 1994, Dharma Rao et al. 2011). Collectively these rocks are referred to as the Bhilwara Supergroup and range between ~3500 and 2700 Ma (Gupta et al. 1980; Table 1). The Aravalli Terrane belongs to Paleoproterozoic era and is mostly made of low grade rocks namely basal synrift basic volcanics, stromatolitic phospherite beds, metapelites, dolomites and quartzites (1762 Ma, McKenzie et al. 2013). The Aravalli basin closed at the end of Paleoproterozoic; altered ophiolites bearing Rakhabdev shear zone represents the subduction zone of the Terrane (Deb et al. 1989; Sarkar et al. 1989; Sugden et al. 1990; Verma and Greiling 1995). Synchronous to closing of Aravalli basin, the North Delhi Terrane was developed in form of several isolated basins of quartzite and phyllites around Jaipur, Khetri and New Delhi (~1712, 1854 Ma, Kaur et al.

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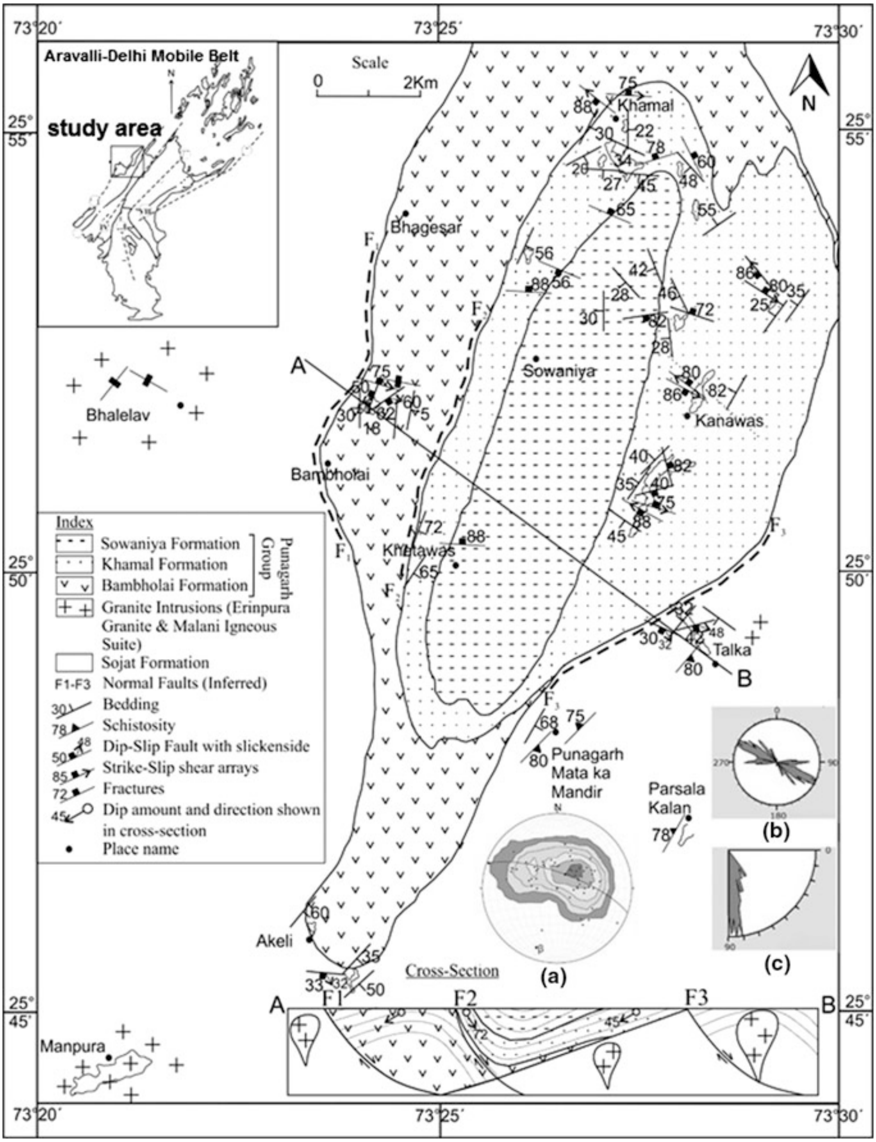


**Fig. 1** Geological map of Punagarh basin (modified after Chore and Mohanty 1998; Van Lente et al. 2009). Inset shows the Aravalli terrane and location of study area. The cross-section shows AB profile; along the profile F1, F2 and F3 are ahown suggesting a half graben structure for the Punagarh basin bounded by easterly dipping faults. **a** Variation in strike and dip of the beds of the Punagarh group rocks is projected on the equal area projection suggesting that the basin is a gentle southward plunging fold. Total number of bedding planes (n) is 60. The trend of best fit great circle is 289 with a dip of 73 NE. Trend of the fold axis, **b** is 199 with a plunge of 17 (bedding plane data given in Table 1), **b** and **c** stereographic projections showing strike directions and dip amounts of fracture planes in the cover rocks respectively

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**Table 1** Variation in bedding plane dip in Punagarh group rocks

| No. | Strike | Dip | Dip direction |
|---|---|---|---|
| 1 | 180 | 30 | W |
| 2 | 178 | 35 | W |
| 3 | 185 | 18 | W |
| 4 | 210 | 82 | NW |
| 5 | 171 | 48 | W |
| 6 | 152 | 43 | SW |
| 7 | 155 | 46 | SW |
| 8 | 216 | 17 | NW |
| 9 | 235 | 50 | NW |
| 10 | 005 | 28 | E |
| 11 | 000 | 22 | E |
| 12 | 024 | 56 | SE |
| 13 | 020 | 55 | SE |
| 14 | 010 | 58 | SE |
| 15 | 025 | 50 | SE |
| 16 | 024 | 55 | SE |
| 17 | 020 | 30 | SE |
| 18 | 025 | 25 | SE |
| 19 | 015 | 32 | SE |
| 20 | 040 | 65 | SE |
| 21 | 045 | 30 | SE |
| 22 | 043 | 34 | SE |
| 23 | 040 | 30 | SE |
| 24 | 090 | 24 | S |
| 25 | 078 | 32 | S |
| 26 | 040 | 45 | SE |
| 27 | 045 | 30 | SE |
| 28 | 080 | 25 | S |
| 29 | 060 | 28 | SE |
| 30 | 060 | 30 | SE |
| 31 | 170 | 25 | W |
| 32 | 147 | 35 | SW |
| 33 | 085 | 28 | S |
| 34 | 062 | 33 | SE |
| 35 | 290 | 50 | NE |
| 36 | 145 | 24 | SW |
| 37 | 095 | 25 | S |
| 38 | 210 | 45 | NW |
| 39 | 130 | 25 | SW |
| 40 | 190 | 30 | W |
| 41 | 158 | 42 | SW |

(continued)

**Table 1** (continued)

| No. | Strike | Dip | Dip direction |
|---|---|---|---|
| 42 | 125 | 25 | SW |
| 43 | 112 | 38 | SW |
| 44 | 138 | 28 | SW |
| 45 | 138 | 33 | SW |
| 46 | 155 | 25 | SW |
| 47 | 175 | 22 | W |
| 48 | 170 | 37 | W |
| 49 | 160 | 25 | SW |
| 50 | 180 | 30 | W |
| 51 | 180 | 40 | W |
| 52 | 225 | 50 | NW |
| 53 | 232 | 43 | NW |
| 54 | 180 | 22 | W |
| 55 | 155 | 30 | SW |
| 56 | 145 | 40 | SW |
| 57 | 118 | 35 | SW |
| 58 | 110 | 45 | SW |
| 59 | 100 | 50 | S |
| 60 | 138 | 50 | SW |

2011, 2013). Contrary to this, the South Delhi Terrane is linear and bears oceanic signature; it extends from Ajmer to Ambaji and is represented by rift volcanics, pillowed basalt, extensive Passive Continental Margin deposits (Biswal et al. 1998). The Terrane opened up in around 1200 Ma (Singh et al. 2010) when rhyolite, diorite and plagio-granites have been emplaced into the basin (c.a. 1000 Ma, Volpe and Macdougall 1990; Deb and Thorpe 2001; Dharma Rao et al. 2013). Phulad ophiolites represent the obducted oceanic crust. The South Delhi basin closed by subduction producing island arc in form of Sendra granites, Erinpura granite and Malani Igneous Suite between 860 and 780 Ma (Crawford 1975; Choudhary et al. 1984; Deb and Thorpe 2001; Singh et al. 2010; Just et al. 2011; Meert et al. 2013).  The change over from orogenic cycle of basin evolution and inversion to the phase of anorogenic magmatism, which is generally bimodal, but dominantly acidic in character (Bose 1989; Bhushan 1995, 2000) along with anorogenic evolution of ephemeral basins, has been recorded in the Trans-Aravalli terrane. The Sirohi Terrane occurs to the west of the South Delhi Terrane, in form of isolated outcrops within vast stretch of Erinpura granites, extending from Sirohi to Sojat and further north (Tosam). Sirohi Terrane is apparently equivalent in age with the South Delhi Terrane (Tosam area, 818 and 793 Ma; Murao et al. 2000; ~992 and 800 Ma of granite gneisses, Purohit et al. 2012; Dharma Rao et al. 2013). The Sindreth and Punagarh basins of ~765 Ma age overlie the Sirohi Terrane and Erinpura granites; these probably constitute part of a back arc basin (Van Lente et al. 2009; Dharma

Rao et al. 2011). The unmetamorphosed and undeformed volcano-sedimentary succession in the Pali region is described as Punagarh Group. Bimodal volcanism in Punagarh basin marks the onset of anorogenic magmatism.

## Study Area

The Punagarh Group was interpreted as the youngest member of Delhi Supergroup (Gupta et al. 1997; Sinha-Roy et al. 1998; Roy and Jakhar 2002). However, Bose (1989) suggested that these volcano-sedimentary sequences possibly deposited in the time gap between the Delhi Orogeny and the Malani volcanism (Delhi orogeny, ca 850 Ma, Choudhary et al. 1984; Malani Igneous Suite, ca 771–751 Ma; Chore and Mohanty 1998; Torsvik et al. 2001). The Punagarh Group unconformably overlies the Sojat Formation with an angular unconformity at the base. The Sojat Formation is represented by folded and metamorphosed rocks namely slate, phyllite and schist that have been intruded by Erinpura granites and Malani Igneous Suite. However, the Punagarh Group is free from any granitic intrusion. It is subdivided into three formations viz. Bambholai Formation, Khamal Formation and Sowaniya Formation consisting of quartzite, shale and bimodal volcanics. The Punagarh basin evolved as an asymmetric half graben with steeper western flank and outpouring of mafic volcanics of Bambholai Formation was facilitated by these graben related faults (Chore and Mohanty 1998). The Sojat sediments are modeled with Archean gneisses whereas Punagarh group sediments indicate Mesoproterozoic Delhi arc related to back-arc setting based on the provenance analysis using trace elements and petrography (Khan and Khan 2015). A reactivated rift environment (Pali lineament) in response to a plume activity was suggested for Bambholai volcanics based on the general geology, geochemistry and associated lithology (Khan et al. 2004). However, Van Lente et al. (2009) discarded the idea of plume related activity or continental rifting based on the presence of hydrothermally altered basaltic pillow lavas and proposed that low grade alteration features present in the Punagarh basaltic rocks formed as a result of hydrothermal processes associated with basalt–seawater interaction in newly formed oceanic crust favoring a back-arc setting.

In this paper we have attempted a large scale mapping of the Punagarh Group and interpretation of structural data. Number of normal faults and strike slip faults has been identified in small to outcrop scale based on brecciation, slickenlines and flanking structure. Based on these small scale structures, we have interpreted large scale structure of the basin. Fault plane analysis has been done using slickenlines and paleostress have been deduced. This helps in understanding the tectonic evolution of the trans-Aravalli terrane.

**Table 2** Normal fault planes with sliplines (slickensides)

| No. | Fault plane | | Slickensides | |
|---|---|---|---|---|
| | Strike | Dip | Trend | Plunge |
| 1 | 200 | 50 NW | 282 | 50 |
| 2 | 176 | 86 W | 241 | 86 |
| 3 | 190 | 65 W | 252 | 62 |
| 4 | 175 | 42 W | 242 | 40 |
| 5 | 210 | 46 NW | 272 | 43 |
| 6 | 022 | 62 SE | 091 | 61 |
| 7 | 034 | 70 SE | 110 | 70 |
| 8 | 030 | 88 SE | 120 | 88 |
| 9 | 020 | 82 SE | 095 | 82 |
| 10 | 005 | 88 E | 090 | 88 |
| 11 | 008 | 75 E | 063 | 72 |
| 12 | 055 | 75 SE | 117 | 73 |
| 13 | 165 | 82 E | 107 | 81 |
| 14 | 075 | 40 SE | 140 | 37 |
| 15 | 045 | 52 SE | 107 | 49 |
| 16 | 070 | 46 SE | 132 | 43 |
| 17 | 020 | 65 SE | 081 | 62 |
| 18 | 038 | 75 SE | 099 | 73 |
| 19 | 025 | 70 SE | 081 | 72 |
| 20 | 111 | 35 SW | 191 | 35 |
| 21 | 114 | 30 SW | 197 | 30 |
| 22 | 115 | 28 SW | 203 | 28 |
| 23 | 110 | 29 SW | 197 | 29 |
| 24 | 108 | 26 SW | 197 | 26 |
| 25 | 280 | 26 S | 193 | 26 |
| 26 | 275 | 35 S | 191 | 35 |
| 27 | 246 | 54 W | 307 | 50 |
| 28 | 245 | 47 W | 330 | 47 |
| 29 | 95 | 33 S | 167 | 32 |
| 30 | 58 | 54 SE | 103 | 45 |
| 31 | 95 | 42 N | 028 | 40 |

## Rock Types

(i) *Basement*: The Sojat Formation is represented by a succession of variegated slate, phyllite, schist, metatuff, sheared quartzite and ferruginous and brecciated quartz rock. The best exposures of Sojat Formation are seen at Sojat fort hill and Punagarh hill. Thick quartz veins are intruded within Sojat slate and phyllite. The schists consist of elongated quartz grains embedded inside biotite matrix. The biotites are aligned parallel to axial plane cleavage of $F_1$ fold.

**Table 3** Conjugate shear planes (conjugate en-echelon quartz vein arrays)

| No. | Shear plane 1 (dextral sense of shear) | | | Shear plane 2 (sinistral sense of shear) | | |
|---|---|---|---|---|---|---|
| | Strike | Dip | Dip direction | Strike | Dip | Dip direction |
| 1 | 100 | 76 | NE | 135 | 85 | SW |
| 2 | 100 | 78 | NE | 130 | 88 | SW |
| 3 | 120 | 80 | NE | 150 | 86 | SW |
| 4 | 120 | 74 | NE | 150 | 82 | SW |
| 5 | 110 | 70 | NE | 140 | 80 | SW |
| 6 | 112 | 76 | NE | 145 | 85 | SW |
| 7 | 120 | 74 | NE | 150 | 85 | SW |
| 8 | 118 | 80 | NE | 150 | 86 | SW |
| 9 | 115 | 72 | NE | 155 | 78 | SW |
| 10 | 110 | 75 | NE | 153 | 88 | SW |
| 11 | 112 | 78 | NE | 158 | 88 | SW |
| 12 | 105 | 70 | NE | 135 | 75 | SW |
| 13 | 100 | 72 | NE | 130 | 78 | SW |
| 14 | 140 | 70 | NE | 090 | 74 | SW |
| 15 | 115 | 72 | NE | 138 | 78 | SW |
| 16 | 105 | 80 | NE | 140 | 84 | SW |
| 17 | 110 | 74 | NE | 140 | 86 | SW |
| 18 | 120 | 76 | NE | 148 | 88 | SW |

Hence it has been interpreted that a greenschist facies metamorphism has occurred during $F_1$ stage of folding. Crenulation cleavage has been developed during $F_2$ folding (Fig. 2a). The other rock type in Sojat Formation is the metatuff that is dark coloured and carries feldspar crystals floating in fine grained matrix. The Sojat rocks are intruded by melanocratic, coarse to medium grained granodiorite at Talka and leucocratic, coarse grained, felsic porphyritic granite near Manpura (Fig. 2b, c respectively). The granodiorite consists of plagioclase, quartz, hornblende, biotite and opaques. The rock has been dated to be ca 800 Ma (Choudhary et al. 1984). The granites are of two types; one abundant with perthite texture and the other lack perthites altogether.

(ii) *Cover rocks*: Bambholai Formation is the lowest formation in Punagarh Group. It mainly contains pillow basalts with interlayered quartzite and shale beds and it extends from north of Khamal to south of Akeli. Three major lava flows have been delineated based on interflow meta-sediments. The lowermost flow shows few isolated pillows enclosed in subaqueous breccia while upper flows are mostly pillow breccia showing isolated and close packed pillows. The cross-section of pillows is circular to elliptical with a size ranges from 50 cm to 1.5 m. The ratio of longer to shorter axis does not exceed 2.5:1. Undeformed pillows with chilled margins and radial cracks are common. The

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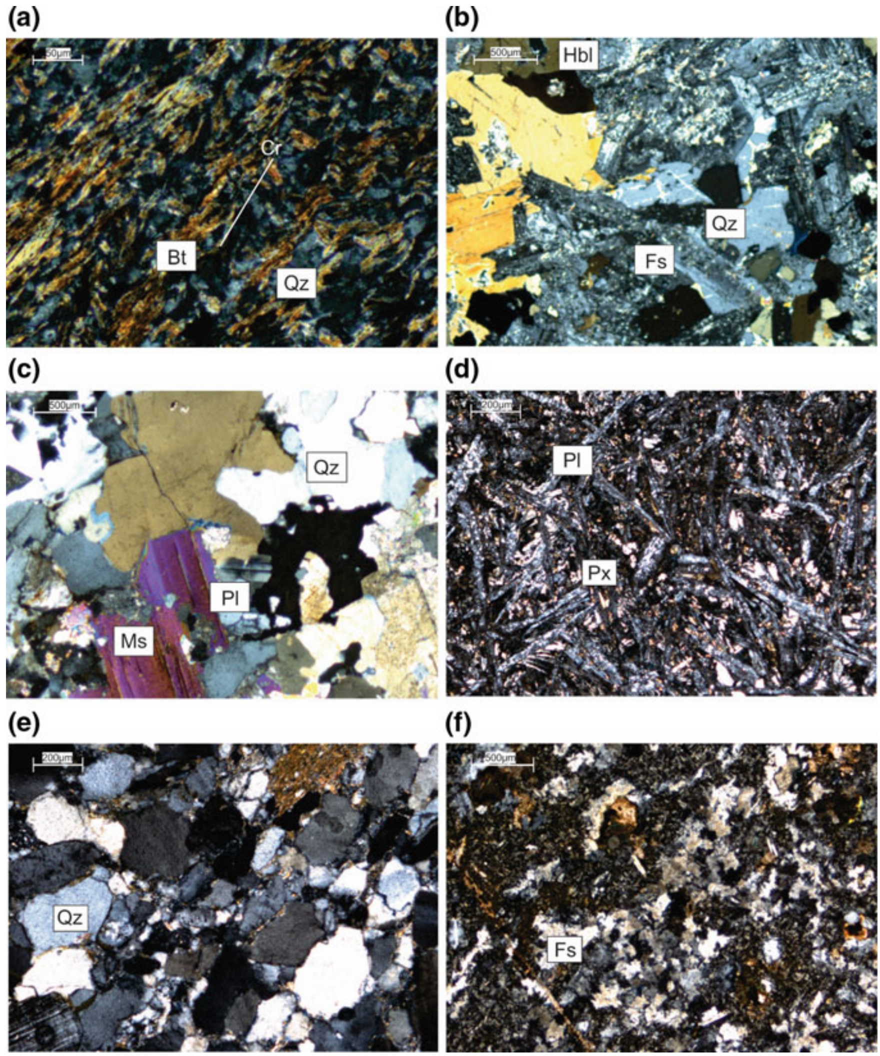


**Fig. 2** Photomicrographs, Abbreviations used: Qz—Quartz, Bt—Biotite, Fs—Feldspar, Pl—Plagioclase, Ms—Muscovite, Hbl—Hornblende. **a** Crenulation cleavage (Cr) in Sojat schist, **b** granodiorite intruded in Sojat Formation, **c** granite intruded in Sojat Formation, **d** basalt of Bambholai Formation, **e** quartzite of Khamal Formation, **f** dacite of Khamal Formation



aphanitic lower flow with numerous hyaloclastic bands is separated from middle flow by a thin band of grey jaspery quartzite. Vesicles and amygdules of variable size and shape are common. Basalt shows porphyritic, hyalophitic, intergranular and intersertal texture. Basalt is highly altered to some clay minerals. Minor relict magmatic compositions are preserved. Olivine and plagioclase occur as phenocrysts. Large slender plagioclase laths often showing flow texture are embedded in an altered groundmass containing fine plagioclase microlites. The interspaces created by plagioclase laths are filled with glass, iron oxide (Fig. 2d). Quartzite carries angular to sub-rounded grains with large volume of argillaceous matrix. This indicates low maturity. The Khamal Formation is dominated by quartzite with interbedded chert, shale and dacitic flows. Greenish grey quartzite contains rounded to sub-rounded quartz in siliceous matrix suggesting higher maturity (Fig. 2e). Lithic fragments of about 1 cm in size are ubiquitous. Vesicular and amygdule structures are common in dacitic flows. Dacite shows intergranular texture and contains plagioclase laths in a quartzo-feldspathic groundmass (Fig. 2f). Sowaniya Formation mainly comprises fine to medium grained clastics represented by shale, gritty quartzite and metabasic syn-sedimentational flows. Quartzite contains subrounded lithic clasts of shale and slate. Subrounded to subangular quartz with kaolinised feldspar is present in arenaceous matrix of quartzite with minor sphene, epidote and calcite. The syn-depositional mafic and felsic volcanic flows are represented by basalt and rhyolite respectively. Basalt has often preserved pillow structure with a size of an individual pillow varying from 0.5 to 2 m across. Basalt shows hyalophitic texture with large oligoclase-andesine laths present in the altered glassy groundmass. Alteration is a common feature. Well preserved banding and vesicular structures are often observed in interlayered rhyolite. Rhyolite contains euhedral phenocrysts of quartz and feldspar in a fine grained groundmass. Shale exhibits different colors as irregular patches or streaks. Punagarh group of rocks have been intruded by several mafic and felsic dykes. Large hornblende crystal derived from partly alteration of clinopyroxene partially enclosed plagioclase laths giving sub-ophitic to ophitic texture to the dolerite. Felsic dykes which are rhyolitic in composition contain phenocrysts of feldspar in fine grained groundmass.

## Deformation Structures

(i) *Basement rocks*: The Sojat Formation has been deformed into small scale tight isoclinal fold and axial plane cleavage developed parallel to these folds in N75E/42SE direction (Fig. 3a). Later these folds have been superimposed by upright inclined folds with crenulation cleavage having trend that varies from N30E/75NW to N30E/85SE (Fig. 3b) Further the rocks have been faulted by many normal listric as well as normal slip faults (Fig. 3c). Deformation in hanging wall of listric faults led to the development of roll over antiforms (Fig. 3d). Roll over antiforms has produced complimentary synforms. At Punagarh hill, ferruginous brecciated quartzite is developed along a N20E/65SE trending normal fault. At Sinla, the rocks are deformed into sheared quartzite along a N30E/65W trending normal fault where down dip

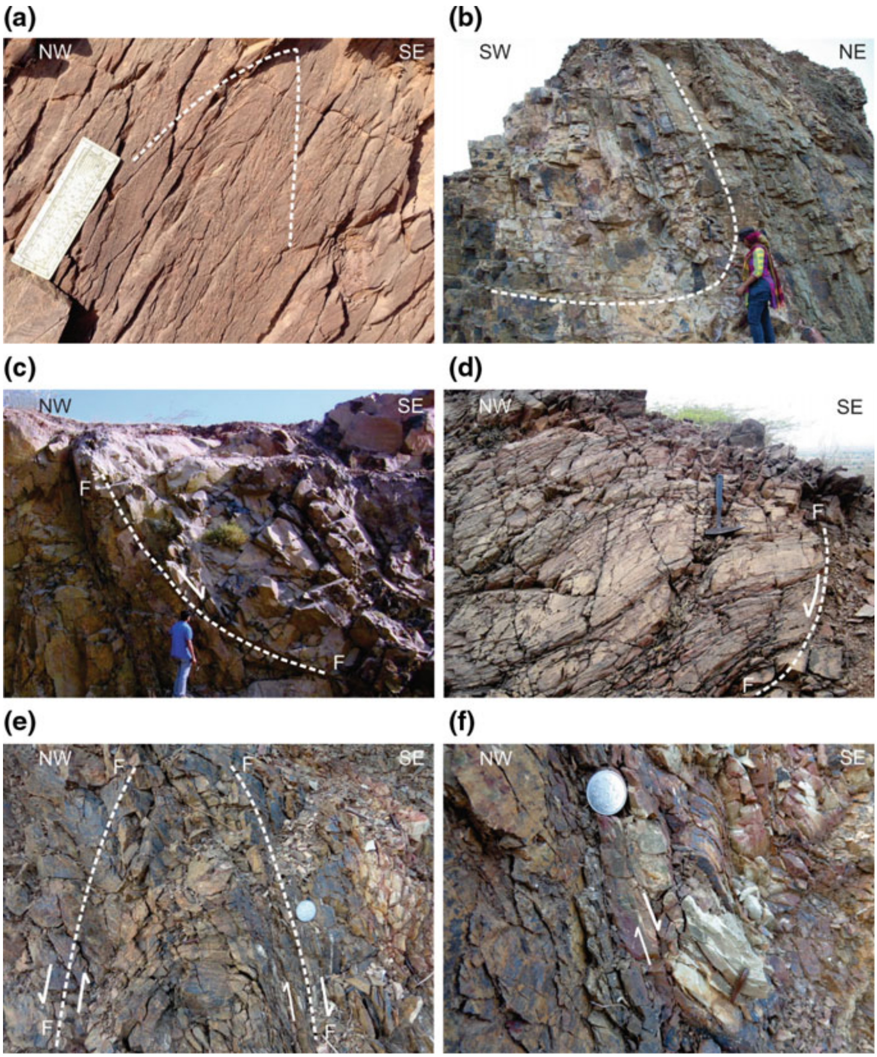


**Fig. 3** Structures in Sojat Formation seen on vertical section. **a** Tight isoclinal fold having axial plane dip N42°/345 within slates, **b** open folds in phyllite at Talka, **c** listric fault with a normal slip, **d** roll over antiform. Structures in Bambholai Formation, **e** antiformal structure developed between two normal faults showing opposite sense of shear, **f** shear band defined by fractured rocks between two shear bands flanking structures are observed



slickensides are observed. In addition to normal slip faults, strike slip faults are also abundantly developed in the quartzite and schists. The strike of such faults varies from N110E to N140E. They behave both in brittle and ductile manner showing both sinistral and dextral sense of shear.

(ii) *Cover rocks*: Punagarh basin shows variation in dip of beds from west to east (Fig. 1) and the variation are shown in equal area projection diagram (Fig. 1a). The fold axis is NE-SW trending with a gentle plunge towards south. This forms a synformal structure within the Punagarh basin. These beds have been transversed by numerous sub-vertical normal faults having NE-SW strike. Near Bambholai shale beds are highly sheared with shear band, brittle S-C structures, antiformal folds and flanking structure (Fig. 3e). The rocks along the shear band are highly fractured and appear almost steep dipping to west as well to east. Between two fault planes, the shale has been dragged along fractures developed due to brittle shearing and thus antiformal structures were formed. These fractures are associated with shear bands and flanking structures (Fig. 3f) that point to normal slip character. Shear bands are brittle in nature and are at low angle to the fault planes with synthetic sense of shear (R shear). Quartzite beds of Punagarh basin are marked with abundant strike slip shear zones hosting en-echelon quartz vein arrays. Dextral and sinistral vein arrays strike N110E and N140E respectively (Fig. 4a). At very few places the vein arrays are sigmoidal (Fig. 4b). Faulting along sinistral vein arrays is very common. Punagarh basin has been intruded by felsic and doleritic dykes parallel to these sinistral strike slip faults.

## Paleostress Reconstruction

Reduced paleostress tensor determination was made by a numerical method, according to the standard procedures (Angelier 1991, 1994; Dunne and Hancock 1994). The inversion is based on the assumption of Bott (1959) that slip on a plane occurs in the direction of the maximum resolved shear stress. Fault and shear plane data were inverted to obtain the four parameters of the reduced stress tensor: the principal stress axes σ1 (maximum compression), σ2 (intermediate compression, σ3 (minimum compression) and the ratio of the principal stress differences $R = (\sigma 2 - \sigma 3)/(\sigma 1 - \sigma 3)$. The latter defines the shape of the stress ellipsoid. These parameters are determined by using successively an improved version of the right dihedral method of Angelier and Mechler (1977), and a four dimensional numeric rotational optimization method, using the TENSOR program (Delvaux 1993). The two additional parameters of the full stress tensor are the ratio of extreme principal stress magnitudes $(\sigma 3/\sigma 1)$ and the lithostatic load, but these cannot be determined from fault data only. Stress regime defines the type of stress tensor. The stress regime is determined by the nature of the vertical stress axes: extensional when σ1 is vertical, strike-slip when σ2 is vertical and compressional when σ3 is vertical. Inside these three major types, the stress regime also varies in function of the stress ratio (R): radial extension (σ1 vertical, $0 < R < 0.25$), pure extension (σ1 vertical, $0.25 < R < 0.75$), transtension (σ1 vertical, $0.75 < R < 1$ or σ2 vertical, $1 > R > 0.75$), pure strike-slip (σ2 vertical, $0.75 > R > 0.25$),

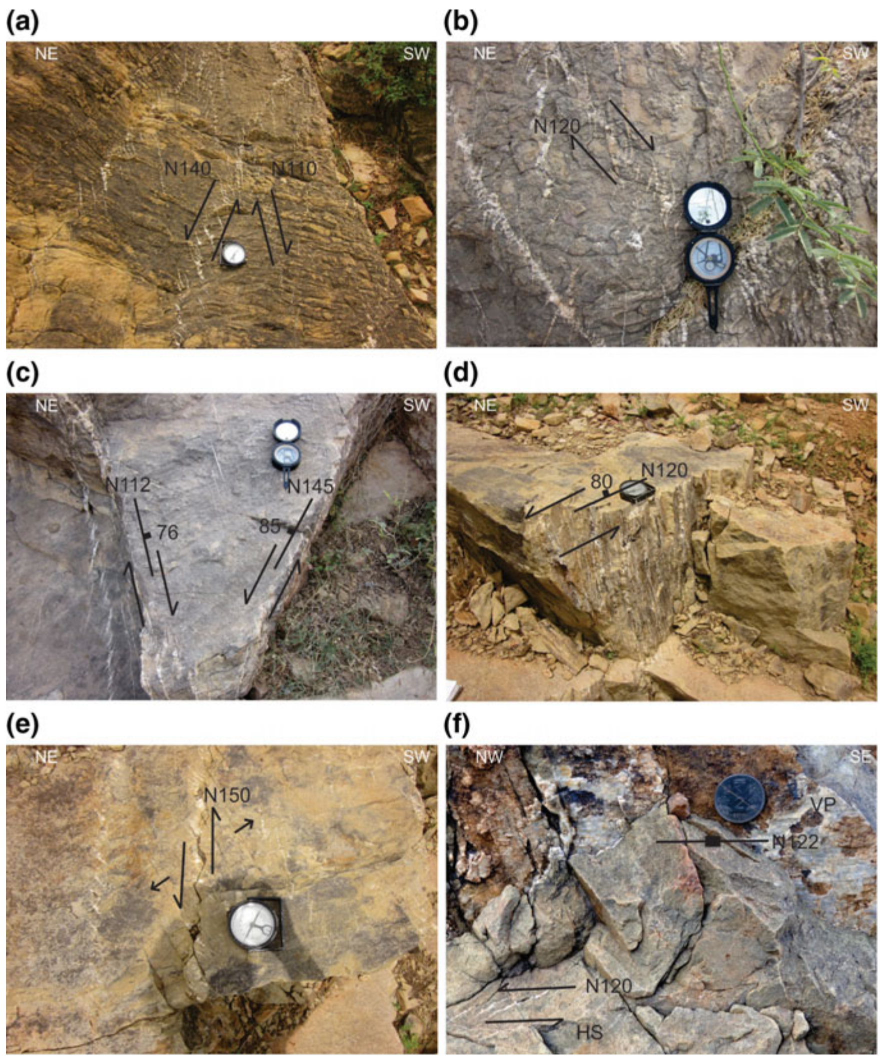


**Fig. 4** **a** Strike-slip conjugate set of en-echelon arrays in quartzite of Punagarh group (horizontal section), **b** sigmodal vein geometry in a sub-horizontal section, **c** fractures along the strike slip shear zones seen in a horizontal section, **d** fracture along the strike slip shear zone seen in a vertical section, **e** strike slip shear along with tension seen on horizontal section of a shear zone, **f** slickenlines on vertical fracture plane (VP) are observed. On horizontal section (HS) en-echelon array is observed showing sinistral sense of shear. Slickenlines are parallel to en-echelon array

transpression ($\sigma2$ vertical, $0.25 > R > 0$ or $\sigma3$ vertical, $0 < R < 0.25$), pure compression ($\sigma3$ vertical, $0.25 < R < 0.75$) and radial compression ($\sigma3$ vertical, $0.75 < R < 1$) (Delvaux et al. 1997).

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*Normal slip faults*: Small scale normal slip faults are abundantly developed within Bhambolai Formation and Sojat Formation. 31 such faults have been analyzed using win-Tensor, software developed by Dr. Damien Delvaux, Royal Museum for Central Africa, Tervuren, Belgium. The plunge and azimuth of σ1, σ2 and σ3 axis is 84/278, 04/046 and 05/136 respectively. This suggests that NW-SE

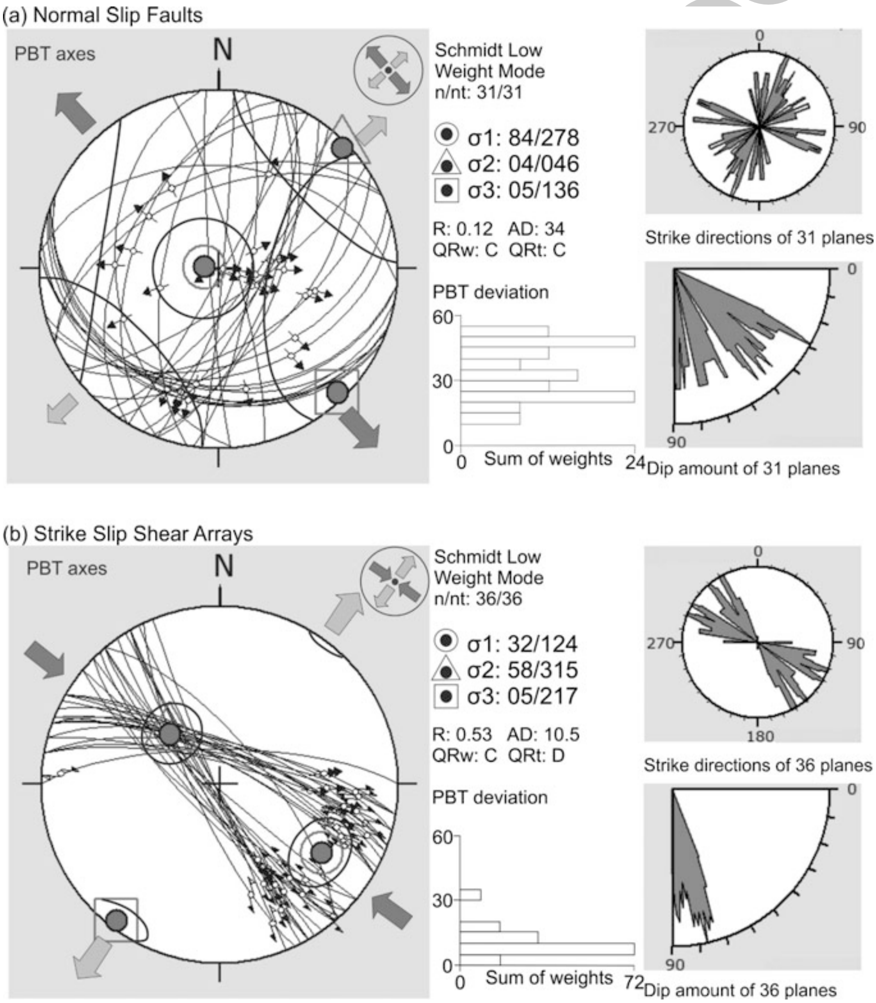


**Fig. 5** Paleostress reconstruction for Punagarh basin using Win-Tensor software (Delvaux). **a** Using normal fault planes (n = 31), σ1: 84/278, σ2: 04/046 and σ3: 05/136 with R = 0.12 suggesting extensional tectonic regime for basin development. Fault plane data has been given in Table 2. **b** Using strike-slip conjugate set of en-echelon arrays of quartz veins (n = 18), σ1: 32/124, σ2: 58/315 and σ3: 05/217) with R = 0.53 suggesting late phase strike-slip tectonic regime. Strike-slip shear array data given in Table 3. Extension direction during normal faulting and compression direction during strike slip faulting remains same

extension has given rise to such faults (Fig. 5a). Radial extensional stress regime is interpreted from stress ratio (R = 0.12).

*Strike slip faults*: Fibrous vein systems are normally developed in rocks of differing competence undergoing deformation in regions of low to middle grade metamorphism. Fibrous vein systems are generally most abundant in the more competent layers of a lithologically stratified succession of rocks (Ramsay and Huber 1983). Numerous arrays of en-echelon quartz filled veins which are aligned in two intersecting directions and dividing the strained rock mass into wedge shaped units have been found in quartzite beds of Punagarh basin (Fig. 4a). The intersection of these en-echelon vein arrays is similar to the patterns formed by conjugate shear planes. The veins in one array are parallel to the conjugate zone and interpreted as shear fractures. These conjugate arrays are classified as Type 1 arrays of Beach (1975). These arrays have been formed during progressive deformation within established shear zones i.e. the fractures are formed after the shear zone. The en-echelon vein arrays are classified as transtensional vein arrays because vein propagate at low angles to the zone (<45°) with an accompanying zone dilation and formation of bridge structures as fracture tips overlap and interact (Beach 1975; Pollard et al. 1982). At many places, faults have developed along the zones of en-echelon vein arrays (Fig. 4c, d). Tensional features along with strike slip shear are also observed in the field showing extension in NNE-SSW (Fig. 4e). Sinistral sense of shear across the fault plane is inferred from the en-echelon arrays parallel to fault planes with slickenlines (Fig. 5f). Conjugate arrays of en echelon veins are one of the kinematic indicators. Mesofracture analysis for the determination of stress or strain trajectories has been extensively studied by Hancock (1985). It is assumed that all the sub-vertical to vertical en echelon vein arrays represented transcurrent dextral and sinistral shear zones. The average dextral and sinistral trends were noted and these directions were bisected. The acute and obtuse bisectors of the dihedral angle between the symmetric shear zones will give the maximum shortening (maximum compression $\sigma 1$) and maximum extension (minimum compression $\sigma 3$) directions and the zonal intersection will give the intermediate strain and stress axis in a fairly homogeneous and isotropic rock. For sites with a single set of fault slip data, 10–50 measurements with a mean number 20–30 suggest good quality rank for tensor analysis. A total set of 18 conjugate shear planes (en echelon arrays) were studied in the cover rocks, and their trends with their dips are plotted in Fig. 5b. The majority of planes of shearing strain fall into two groups with strike of N110E and N150E. The average of principal stress axes direction was calculated on TENSOR program. The plunge and azimuth of $\sigma 1$, $\sigma 2$ and $\sigma 3$ axis is 32/124, 58/315 and 05/217 respectively. The stress tensor is strike-slip type with NE-SW direction of extension and NW-SE is the direction of compression.

## Large Scale Structure

Based on the dip variation and presence of small scale faults, the large scale structure of the basin has been interpreted. The large scale structure is displayed in form of a cross section (AB) in Fig. 1. The basin appears like a half graben bounded by basin margin faults. On the basis of sedimentation characteristics it has been interpreted that the basin becomes deeper towards west. Three map scale faults have been marked, namely F1, F2 and F3. F1 and F3 are basin margin faults and dip towards SE. F2 is within basin fault and could be a propagation fault developed during sedimentation in form of trishear proposed by Khalil and McClay (2002). Across F1 and F3, roll over antifoams are developed while across F2, drag folds are developed. Because of these fault related folds the Punagarh Basin appears like a synformal structure on the map. The synform plunges to south. In the map an elliptical pattern has been shown. However, the southern closer is due to topography. AQ3

## Discussion

The trans-Aravalli region is the detached fragment of Arabian Nubian Shield which accreted with southern and western Indian shield at about ca 860 Ma (Singh et al. 2010). A connection between Punagarh, Sindreth and Malani volcanism had been suggested on geological grounds by Roy and Sharma (1999). Punagarh volcanics are younger than 800 ± 2.4 Ma, the age of mafic tonalite (but normatively it is a quartz monzodiorite) containing about 17% hornblende and chloritized biotite represents the basement upon which the Punagarh lavas were erupted (Van Lente et al. 2009). The evolution of these basins is debatable. Sojat Formation which forms the basement of the Punagarh basin represents the youngest member of Delhi Supergroup. Ductile deformation in the form of open folds in the Sojat Formation marks the culmination of Delhi orogeny. It is followed by Erinpura magmatism which is manifested as intrusive relationship with the Sojat Formation. Van Lente et al. (2009) suggested back arc setting for the Punagah basin. However, the quartzite and the shale formations show higher maturity that may not well supportive of back arc character. Further, Delhi orogeny belongs to 850–830 Ma (Singh et al. 2010) and the basins are much younger. Punagarh Group could be equivalent to Malani Igneous Suite or may represent a time gap between the Erinpura magmatism and Malani volcanism. Our study shows that normal faults are responsible for the development of Punagarh basin. The paleostress analysis of normal faults indicates a NW-SE extension. Hence, extension in above direction produced half graben structures which acted as sedimentary repository. The faults are growth faults and helped in deepening of the basin during deposition. As a result the overlying sediments got faulted and propagated faults are produced. One of the basement faults namely the F2 was reactivated and propagated later in the evolution history, thus producing steeper beds adjoining to it in the form of drag folds. Punagarh basin later was controlled by strike slip tectonics developing NW-SE trending faults. Thus the basin was offset from other basin of Trans-Aravalli terrane. Hence it is isolated from Sindreth and other minor basins. Outpouring of lava took place along the basement faults due to extensional setting. Volcanics of Bambholai and dacites of Khamal Formations are examples of such syn-sedimentary volcanism. Syn-extensional sedimentation would have been focused along the longitudinal axis of the hanging wall synclines, whereas footwall uplift would have produced erosion of the pre rift strata; this resulted in deposition of Sowaniya Formation.

## Conclusion

Detailed field mapping and analysis has demonstrated that the kilometer scale half graben structure that has hosted the Punagarh basin is developed over a granitic-metasedimentary crust. The beds have been folded into a southern plunging syncline due to fault related folding. Extension produced such graben structure; the magmatism is related to extensional setting. Continued NW-SE extension produced strike linkage of the fault system which leads to the formation of asymmetric Punagarh basin. Strike-slip tectonics observed in the form of conjugate shear arrays suggesting NW-SE compression is an indicative of change in stress regime of Punagah basin. From these structures, it is suggested that continental extension subsequent to Delhi Orogeny has produced such basin with volcano-sedimentary sequence which later underwent compression. The abundance of brittle deformation with extension parallel to the Pali lineament suggests that the Punagarh basin probably formed as a result of extension in the Trans-Aravalli terrane by reactivation of faults in Pali lineament.

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