Palaeostress and magma pressure measurement of granite veins in the Neoproterozoic Ambaji granulite, South Delhi terrane, Aravalli–Delhi mobile belt, NW India: Implication towards the extension-driven exhumation of the middle–lower crustal rocks

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Neoproterozoic Ambaji granulite, in the South Delhi terrane (SDT) of the Aravalli–Delhi mobile belt (ADMB), is multiply deformed at different stages of its exhumation from the middle–lower crust. It was intruded by four phases of granites, G_{0-3} , of which the G_3 was syntectonic with brittle shearing. The orientation of the G_3 granite veins was used, in this paper, to measure the palaeostress and magma pressure during its intrusion. The G_3 granite has a porphyritic texture with quartz, microcline and biotite minerals and contains magmatic foliation; biotites are aligned oblique to such foliation, suggesting the syntectonic intrusion of the granite with normal faulting. Stereoplot of the poles of the granite veins shows concentration in the NW and SW quadrants and lack data over an elliptical area at the centre, indicating a girdle pattern. This implies that the magma pressure $P_m > \sigma_2$, compression σ_1 was vertical and extension σ_3 was NW–SE horizontal. Values of $\theta_2 = 16^\circ$ and $\theta_3 = 40^\circ$ were obtained from the stereoplot, used to calculate stress ratio $\Phi = 0.81$, driving pressure $R' = 0.92$ and the construction of the 3D Mohr plot for P_m and principal stresses. Result suggests that the G_3 granite intruded under extensional tectonics that probably contributed to the exhumation of the Ambaji granulite.

Keywords. Palaeostress and magma pressure analysis; G_3 granite vein; extension; exhumation; Neoproterozoic Ambaji granulite; Aravalli–Delhi mobile belt.

1. Introduction

Stress and strain are two fundamental parameters of deformation in the lithosphere. Stress indicates the dynamic part where an external force acts on a rock mass creating deformation. Strain is the kinematic part that includes the change in the shape, size or volume in ductile deformation or rock failure in brittle deformation (Ramsay 1967; Twiss and Moores 2007; Fossen 2010). There are several

methods available in the literature to measure the strain (Ramsay and Huber 1987), but it is challenging to measure the absolute value of stress. The measurement of stress provides information regarding compression, extension and strike slip tectonic settings and helps in understanding the tectonic history of a terrane, like basin formation, inversion of basin, exhumation of deeper rocks, intrusion of dyke and vein, etc. In the literature, several methods have been proposed to measure the stress ratio

$\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ (Angelier 1994; Ramsay and Lisle 2000; Fossen 2010), magmatic pressure P_m relative to the tectonic stress and the driving stress ratio $R' = (P_m - \sigma_3)/(\sigma_1 - \sigma_3)$. This is done in several ways: (i) using grain size and shape in ductile deformation (Stipp *et al.* 2002; Stipp and Tullis 2003); (ii) fault-slip data in brittle deformation (Anderson 1951) and (iii) distribution pattern of dykes and veins (Baer *et al.* 1994; Jolly and Sanderson 1997).

In this paper, palaeostress and magmatic pressure of granite veins have been measured to understand the tectonics of granite intrusion. Our study area belongs to the Neoproterozoic Ambaji granulite which is one of such exhumed blocks within the vast stretch of low-grade rocks of the South Delhi terrane (SDT) of the Aravalli–Delhi mobile belt (ADMB), NW India. Previous studies on the Ambaji granulite include folding, metamorphism, geochemistry, strain analysis of shear zones and palaeostress analysis of faults. In this study, we focus on G_3 granite veins which have intruded during brittle shearing. The orientation of the G_3 veins has been used to deduce the palaeostress and magmatic pressure during its intrusion, using techniques developed by Baer *et al.* (1994) and Jolly and Sanderson (1997). The tectonics of granite intrusion has been correlated with the tectonics of the exhumation of the granulite.

2. Tectonic setting of the Ambaji granulite

2.1 Regional geology

The NE–SW trending ADMB contains several geologically distinct terranes demarcated by shear zones (figure 1a and b; Gupta *et al.* 1980; Singh *et al.* 2010). The terranes are, namely, Archaean Hindoli–Jahajpur, Mangalwar, Sandmata terranes, the Palaeo-Mesoproterozoic Aravalli and North Delhi terranes, and the Neoproterozoic Sirohi and SDT. The Hindoli–Jahajpur terrane consists of greenstone belts, the Mangalwar terrane has a tonalite–trondhjemite–granodiorite (TTG) gneiss and the Sandmata terrane includes granulite facies rocks (Gupta *et al.* 1980; Sinha-Roy 1985; Bhowmik *et al.* 2010). The Aravalli and North Delhi terranes comprise quartzite–pelite–carbonate rocks metamorphosed in greenschist to lower amphibolite facies. Ophiolite-bearing Rakhabdev shear zone in Aravalli and Andean-type continental arc magmatism in North Delhi provides evidence

of subduction during the Palaeo-Mesoproterozoic period (Deb and Thorpe 2001; Kaur *et al.* 2009). The SDT comprises extensive quartzite–pelite–carbonate metasediments with oceanic rocks such as rift-related metabasalt and metarhyolite, diorite and plagiogranite (ca. 1000 Ma; Volpe and Macdougall 1990; Dharma Rao *et al.* 2013). These rocks, by and large, are metamorphosed under greenschist to amphibolite facies. There is a unique occurrence of granulitic rocks near Ambaji (Ambaji granulite) that has been studied in this paper. The sedimentation age in SDT was between ca. 1200 and 860 Ma and the age of metamorphism was ca. 860 Ma (Biswal *et al.* 1998a, b; Singh *et al.* 2010). The Sirohi terrane comprises isolated outcrops of low-grade metasedimentary rocks of ca. 900 and 820 Ma age (Purohit *et al.* 2012; Dharma Rao *et al.* 2013). The Sirohi terrane has undergone multiple phases of deformation and granitic intrusion between ca. 860 and 750 Ma (e.g., Erinpura granite, ca. 860–730 Ma, Crawford (1975); Choudhary *et al.* (1984); Balda granite, ca. 770 Ma, Sarkar *et al.* (1992); Tosham granite, ca. 820 Ma, Murao *et al.* (2000); and Malani igneous suite, ca. 770 Ma, Gregory *et al.* (2009) and de Wall *et al.* (2012, 2014)). The Malani igneous suite is the most prominent among them, which has intruded along extensional fractures (Sharma 2005). Furthermore, Sindreth and Puna-garh basins hosting volcano-sedimentary sequences (ca. 765 Ma) were deposited in the extensional setting (figure 1b; Bhardwaj and Biswal 2018).

2.2 Geology of the Ambaji granulite

2.2.1 Rock types

The Ambaji granulite includes pelitic, calcareous and mafic granulite (figure 2; Biswal *et al.* 1998a, b; Sarkar 2006; Singh *et al.* 2010) with narrow stripes of schist and amphibolite along shear zones. The pelitic granulite is a migmatitic rock (figure 3a); the melanosome contains spinel, cordierite, sillimanite, garnet and biotite and the leucosome contains quartz, plagioclase and K-feldspar. The calcareous granulite shows a rib structure due to differential weathering and contains diopside, scapolite, calcite, plagioclase and wollastonite. The mafic granulite consists of orthopyroxene, clinopyroxene, plagioclase and hornblende; garnet is absent in the assemblage. Relict pods of gabbro and norite, interpreted as the protolith of the mafic granulite occurs in the area (Biswal *et al.* 1998a).

Figure 1. Geological map of the ADMB with different terranes and shear zones: (a) location of Proterozoic mobile belts in India, including the ADMB and (b) simplified map of the ADMB showing different terranes. K – Kaliguman shear zone defines the subduction zone of the SDT (modified after Singh *et al.* 2010).

Figure 2. Geological map of the Ambaji granulate (modified after Singh *et al.* 2010).

2.2.2 Folding-metamorphism

Granulite has undergone three phases of folding (Singh *et al.* 2010). The first phase of folding is represented by isoclinal and recumbent F_1 folds with the NE–SW axis, which was developed on the bedding (S_0) by a sub-horizontal simple shear. F_1 is associated with penetrative axial planar gneissosity, S_1 , which is defined by the parallel arrangement of granulite grade minerals as sillimanite, spinel, cordierite and garnet in pelitic granulite; diopside, plagioclase and wollastonite in calcareous granulite, and orthopyroxene, clinopyroxene and hornblende in mafic granulite. Migmatitic banding was developed parallel to the S_1 fabric (figure 3a). These features suggest that the granulite facies metamorphism and melting of the metasediments were syn- F_1 . The mineral assemblage in the pelitic granulite indicates a PT of $\geq 850^\circ\text{C}$ and 5.5–6.8 kbar for peak granulite facies metamorphism that occurred at the middle–lower crust at nearly 25-km depth (Singh *et al.* 2010). The F_1 folds were coaxially refolded by the NE–SW striking open upright F_2 folds producing a type 3

interference pattern. F_2 folds were produced by the NW–SE compression. Spaced crenulation cleavage, microlithons and a set of shear bands axial planar to the F_2 fold developed during the F_2 folding, defining the S_2 fabric (figure 3a). A number of large-scale syn- F_2 shear zones (figure 2), namely, the Balaram shear zone, Surpagla–Kengora shear zone and SZ-I, SZ-II and SZ-III running for tens of kilometres with thicknesses varying from tens of metres to hundreds of metres, were developed. Shear zones were retrogressive, and hosted greenschist grade mylonite. The mylonite contains subhorizontal stretching lineations defined by stretched quartz and biotite grains. On the XZ section of the mylonite cut parallel to the stretching lineation and perpendicular to mylonitic foliation, the K-feldspar porphyroclasts indicate top-to-the-NW sinistral shearing (figure 3b). Furthermore, multiple phases of pseudotachylites were generated by the frictional melting along the shear zone (figure 3c). Some of them were deformed into ultramylonites. The parallel association of deformed and undeformed pseudotachylites indicates a transitional deformation from brittle to

Figure 3. Field photographs: (a) Pelitic granulite with migmatitic structures, S_1 fabric is indicated by migmatitic layers, the S_1 fabric is folded and sheared parallel to the F_2 fold, vertical section; (b) S_2 sinistral-top-to-NW shear in the Surpagla–Kengora shear zone, indicated by sigma type feldspar porphyroclasts (Fsp), horizontal section; (c) pseudo-tachylite veins (Pt) within G_2 granite mylonite, mafic granulite (Mg) is in contact with G_2 . Pt is deformed as indicated by deformed clasts within it, feldspathisation (Fsp) is present within mafic granulite, vertical section; (d) fracture within G_2 granite, Y shear indicates main shear while R indicates Riedel shear, thin G_3 vein has intruded, minor saussuritisation in the G_2 granite is seen in contact with the G_3 vein, UR – undeformed rock within a network of fractures, horizontal section; (e) near vertical slickenlines defined by dark pulverised material in the G_3 granite, indicating a normal slip, (L), arrows indicate slip direction, vertical section and (f) horizontal slickenlines, marked by arrow, indicate strike slip, vertical section.

ductile and back to brittle regime, suggesting the exposure of a palaeo–brittle–ductile transition zone (e.g. Price *et al.* 2012). Hence the granulite was exhumed from the middle–lower crust to

the BDT zone during the F_2 folding. Exhumation produced a decompression texture in the granulite; smaller cordierite and spinel grains developed around the F_1 garnet porphyroblasts, and kyanite

and andalusite were developed from F_1 -sillimanite. Subsequently, NW–SE striking upright large wavelength F_3 folds developed due to the NE–SW compression that brought a large-scale variation in the strike of the litho units and shear zones, and a reversal of the plunging of the F_1 and F_2 folds producing Type 1 and Type 2 interference patterns. Granulites are marked by several sets of faults and fractures, the Kui–Chitraseni fault and Surpagla–Kengora faults border the granulite block.

2.2.3 Granite and geochronology

Several phases of granite (G_{0-3}) have intruded the granulite. Approximately 960 Ma G_0 granite intruded during sedimentation and was folded and metamorphosed (Singh *et al.* 2010). Approximately 860 Ma G_1 granite intruded during the F_1 folding and is gneissic in character. It occurs as inter-layered bands within metasediments and shows a medium to coarse-grained texture consisting of quartz, feldspar, biotite, garnet and sillimanite. It was produced from the melting of the pelitic granulite (figure 3a). Approximately 840 Ma G_2 granite occurs as veins as well as batholiths showing equigranular and rapakivi texture with quartz, feldspar and biotite minerals (figures 3c and 4b, d). The G_2 intrusion is synkinematic with the F_2 folding; it has metasomatised the adjacent country rock and K-feldspar crystals are crystallised (Fsp) along the foliation plane of the mafic granulite (figure 3c). G_2 is mylonitised along shear zones. Approximately 759 Ma old G_3 granite occurs as veins (figure 4a and b) which is the focus of this study. They have intruded along the faults, fractures and foliations. We have used the orientation of the fractures and granite veins to estimate the palaeostress and magmatic pressure at the time of intrusion of the G_3 granite.

3. Methodology

3.1 Palaeostress analysis

Dykes and veins intrude when the magmatic pressure exceeds the tectonic stress across the weak plane such as the fracture plane. This can be denoted as $P_m \geq \sigma_n$, where P_m stands for magmatic pressure and σ_n stands for normal stress acting on the weak plane (Baer *et al.* 1994; Jolly and Sanderson 1997). The fractures perpendicular to σ_3 were more dilated since σ_3 is the least tectonic stress. The planes at right angles to the σ_2 and σ_1

are the least dilated. When P_m exceeds the value of σ_1 , all fractures are dilated, and veins intrude in several orientations. If $P_m \geq \sigma_2$, veins occur in all other orientations but for horizontal or gentle dipping veins. In that situation in a stereoplot, veins are plotted near the periphery and remain absent over the elliptical area in the centre (Jolly and Sanderson 1997; Mondal and Mamtani 2013; Martinez-Poza *et al.* 2014). This is known as the girdle distribution pattern. The centre of the void area indicates σ_1 . The minimum angle between the dilated fracture and the σ_1 and σ_2 direction (θ_2 , θ_3 , respectively) can be measured from the stereoplot. If $P_m < \sigma_2 > \sigma_3$, poles of the veins show clustering around σ_3 axis. In that situation, the minimum angle between the dilated fracture and σ_2 and σ_3 direction (θ_1 , θ_2 , respectively) can be measured. Depending upon the relative value of P_m with tectonic stress, different stereoplots are obtained. Stereoplot provides θ_1 , θ_2 and θ_3 values which are used to construct the 3D Mohr plot to display the P_m values with respect to σ_1 , σ_2 and σ_3 . Furthermore, the stress ratio ‘ Φ ’ for different situations can be computed from the following equations (Jolly and Sanderson 1997; Mondal and Mamtani 2013; Martinez-Poza *et al.* 2014):

For $P_m < \sigma_2$,

$$\begin{aligned}\Phi &= (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3) \\ &= (1 + \cos 2\theta_2)/(1 + \cos 2\theta_3).\end{aligned}\quad (1)$$

For $P_m > \sigma_2$,

$$\begin{aligned}\Phi &= (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3) \\ &= 1 - \{(1 - \cos 2\theta_2)/(1 - \cos 2\theta_3)\}.\end{aligned}\quad (2)$$

The driving pressure ratio R' that describes the magnitude of the magmatic pressure relative to the tectonic stress is given by the formula (Jolly and Sanderson 1997)

$$R' = (P_m - \sigma_3)/(\sigma_1 - \sigma_3) = (1 + \cos 2\theta_2)/2. \quad (3)$$

The above principle has been applied by several researchers to perform palaeostress analysis (e.g., André *et al.* 2001; McKeagney *et al.* 2004; Mazzarini and Isola 2007; Mazzarini *et al.* 2011; Mondal and Mamtani 2013; Martinez-Poza *et al.* 2014; Lahiri and Mamtani 2016). We measured the attitude of fractures and granite veins in the field and plotted poles, in a stereonet. Post- G_3 fractures,

Figure 4. (a) Field photographs of NE – moderately inclined G_3 granite veins cross-cutting the G_2 granite near Kengora, vertical section; (b) two sets of G_3 veins (NE, NW striking) cross-cutting the G_2 granite, one set shows magmatic foliation (Mf), horizontal section, (c) G_3 granite veins showing magmatic foliation (Mf) defined by parallel arrangement of quartz, feldspar (Fsp) and biotite in layers, (d) NW- G_3 granite vein in the G_2 granite, contact is marked by a red-dashed line, G_3 contains magmatic foliation (Mf), biotite grains (Bt) in the magmatic layer are obliquely arranged to magmatic foliation (Mf), suggesting a normal slip, marked by a red arrow, vertical section; (e) a photomicrograph showing magmatic foliation (Mf) due to the alignment of quartz (Qtz), feldspar (Fsp) and biotite grains, undulose extinction is seen in quartz due to high temperature deformation during the intrusion of the G_3 granite syntectonic to normal slip, but there is no dynamic recrystallisation and (f) the hypidiomorphic texture in the core of the G_3 granite (Mc: microcline, Pl: plagioclase and Qtz: quartz).

which cross-cut the granite veins, were excluded from the analysis as far as possible.

4. Results

4.1 Faults and fractures

We used the geological map prepared by Singh *et al.* (2010) for plotting the faults, fractures and granite veins (figure 2). Two major normal faults, namely, the NE–SW to the NNW–SSE Surpagla–Kengora fault and the NE–SW Kui–Chitraseni faults are located in the east and west margin of the granulite block (figure 2). They are inclined away from the granulite block giving rise to a horst structure to the block. In addition to these boundary faults, several internal faults in the WNW–ESE and NE–SW directions occur in the area. The width of the faults and fractures vary from a few millimetres to metres. Fault outcrops are characterised by blocky rocks traversed by several fractures (figure 3d; Riedels, Y shears). They host cataclasites containing angular clasts set within a glassy to an ultra-comminuted matrix. Thin films of dark pulverised material form slickenlines on the fracture surface, in addition to the ridges in groove lineations (figure 3e and f). Mineral growth is rarely seen along the fracture. Between the sets of fractures, islands of undeformed rock occur (figure 3d). It is therefore interpreted that the faulting has taken place within a purely brittle zone. Two types of slickenlines are observed. Vertical slickenlines correspond to a normal slip (figure 3e); there are also horizontal slickenlines indicating a strike slip (figure 3f). In several occasions, the overprinting of the vertical lineation on the horizontal lineation has been preserved, suggesting the normal slip was post-kinematic to the strike slip. Stereoplot of poles to 1162 faults and fractures shows random distribution (figure 5a) and the Rose diagram reveals the NE–SW prominent orientation and the NW–SE is subordinate (figure 5c). A preliminary study suggests that the NW–SE extension was probably responsible for brittle faulting. The faults and fractures are intruded by G_3 granite veins (figure 3d), showing saussuritisation at places (figure 3d).

4.2 G_3 granite veins

Multiple phases of G_3 granite veins have intruded the granulites and G_{0-2} granites along pre-existing

fractures (figure 4a and b). These are abundant around Dhanpura, Padni, Kengora and Bhaisasinga areas (figure 2). We have analysed the granite veins of Dhanpura, Padni and Kengora areas for their close proximity. Stereoplot and Rose diagram of 698 veins suggest that the NE–SW and NW–SE sets are more prominent (figure 5b and d). The veins mutually cross-cut each other suggesting their broad synchronous character (figure 4b). Veins are steep to moderately inclined; horizontal/subhorizontal veins are absent. The veins have tabular geometry; the width of the veins varies from a few centimetres to tens of metres and the strike-length varies from a few metres to a kilometre. In many instances, the veins contain magmatic foliation/layering parallel to the vein wall, produced from the shapes of preferred orientation of quartz, plagioclase, microcline and biotite phenocrysts (figure 4c and d). The biotite grains are concentrated in layers where the individual grains have been obliquely arranged to magmatic foliation consistent with the normal slip (figure 4d). Furthermore, plagioclase and quartz from the vein margin display undulose extinction suggesting solid-state deformation; however, there is no dynamic recrystallisation (figure 4e). The core of the veins preserves the hypidiomorphic and porphyritic texture (figure 4f). Furthermore, fractures are developed close to the vein margin parallel to magmatic foliation, and the vein walls have been marked by normal slip slickenlines (figure 4e). Based on these features, we interpret that the intrusion of the G_3 granite is syntectonic with normal faulting.

4.3 Palaeostress

Stereoplot for fracture planes produced distribution all over the net (figure 5a) while G_3 granite veins showed a girdle pattern with an elliptical void area at the centre (figure 5b). Girdle pattern suggests the magnitude of magmatic pressure $P_m > \sigma_2$. Following Jolly and Sanderson (1997), the centre of the ellipse represents σ_1 direction, the σ_3 lies at the highest cluster in the NW part of the plot and σ_2 lies on the great circle passing through the longer dimension of the ellipse.

From figure 5(b), $\theta_2 = 16^\circ$ and $\theta_3 = 40^\circ$ were obtained; these are the angles between the pole of the dilated fracture planes with σ_1 on the σ_3 – σ_1 and σ_2 – σ_1 planes, respectively.

Figure 5. Palaeostress determination from the G₃ granite veins: (a) stereoplot of poles of fractures (1162 data) in the granulite and the G₀₋₂ granites show orientation in all directions, some are even horizontal; (b) stereoplot of poles of the G₃ granite veins (698 data) shows prominent NE-SW and NW-SE directions, with a subordinate amount in other directions, horizontal veins are absent indicated by the elliptical void area at the centre, and this is known as girdle distribution, which means the horizontal fractures are not dilated, and the centre of the ellipse represents σ_1 direction, σ_3 lies in the NW-SE quadrants, σ_2 in the NE-SW quadrants, $\theta_2 = 16^\circ$, $\theta_3 = 40^\circ$ are measured from ellipse axes and $\Phi = 0.81$ is calculated from equation (1); (c) Rose diagram for fractures and faults (1162), the NE-SW direction is more prominent than the NW-SE direction, (d) Rose diagram for the G₃ granite veins (698), NE-SW and NW-SE directions are prominent and (e) 3D Mohr plot for the G₃ granite veins, θ values are obtained from figure b. $R' = 0.92$ is calculated from equation (3). The P_m field is shaded. P_m value exceeds that of σ_2 but is less than σ_1 . (On the procedure to draw the figure, refer to the text.)

For $P_m > \sigma_2$,

$$\begin{aligned}\Phi &= (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3) \\ &= 1 - \{(1 - \cos 2\theta_2)/(1 - \cos 2\theta_3)\} = 0.81, \\ R' &= (P_m - \sigma_3)/(\sigma_1 - \sigma_3) = (1 + \cos 2\theta_2)/2 = 0.92.\end{aligned}$$

Hence $R' > \Phi$. This indicates that the G_3 granite was emplaced in an axial tension setting implying vertical compression and horizontal extension in all directions. However, from the data concentration in figure 5(b), the NW–SE was the dominant extension direction. The θ_2 and θ_3 angles were used to construct a 3D Mohr plot. An arbitrary circle was drawn between σ_3 and σ_1 (figure 5e) and $2\theta_2 = 32^\circ$ had been plotted in the above circle, and point p' was obtained. Fractures making a higher angle were dilated. The P_m value was obtained from the projection of p' on the horizontal axis; accordingly, the P_m field was shaded. Another circle was drawn between σ_2 and σ_1 in such a manner that when the $2\theta_3 = 80^\circ$ angle was plotted, the point q' would lie on the same alignment as p' , so that fractures making a higher angle would be dilated. The figure indicates $P_m > \sigma_2 < \sigma_1$.

5. Discussion

5.1 Stress pattern

The Ambaji granulite represents the middle–lower crustal rocks in the entire 800 km stretch of the low-to-medium grade SDT. The maximum extension during the G_3 intrusion lay in the NW–SE direction. The majority of the granite veins intruded in NE–SW direction as the fractures in that direction were most dilated. The next major set of veins were in the NW–SE direction right angle to σ_2 direction. As the P_m exceeded σ_2 value, fractures in that direction were also dilated. Gentle dipping fractures ($<16^\circ$) did not dilate as they were making a high angle with σ_1 which was $> P_m$. Girdle pattern ($R' > \Phi$) indicates $P_m > \sigma_2 < \sigma_1$. The stress ratio $\Phi = 0.81$ and the driving stress ratio was 0.92 suggesting axial tension. Hence, the granulitic crust was undergoing an axial tension, dominantly in the NW–SE direction, during the intrusion of the G_3 granite.

5.2 Tectonic implications

Ambaji granulite was metamorphosed under granulite facies at ca. 860 Ma in a compressive setting

during the South Delhi orogeny (Biswal *et al.* 1998a,b; Singh *et al.* 2010). NW–SE shortening during the F_1 and F_2 folding, plutonism due to G_2 intrusion and transpression during S_2 shearing thickened the crust and built the great height of the orogen. Thickening of the crust accompanied by denudation brought the first stage of exhumation/uplift to a 15-km depth. This is evident in the mineral assemblages of the decompressed granulite and the brittle–ductile S_2 shear zones. Subsequently, granulite underwent extensional tectonics and developed faults and fractures. G_3 granite was intruded along these faults and fractures. Palaeostress analysis suggests axial extension (dominantly the NW–SE extension) during the G_3 intrusion.

Several mechanisms have been explained for the exhumation of deeper rocks, e.g., granite intrusion and vertical thrusting (e.g., Hill *et al.* 1995; Ring *et al.* 1999), transpressive shearing in a zone of oblique convergence (e.g., Sylvester and Smith 1976; Sanderson and Marchini 1984; Fossen and Tikoff 1993; Martelat *et al.* 1997; Thompson *et al.* 1997) and crustal extension causing stretching and tectonic denudation (e.g., Dewey 1988; Dewey *et al.* 1998). Exhumation of the Ambaji granulite consists of two stages, in the first, it was exhumed by thrusting to the BDT zone. Second, in the brittle crust, the exhumation took place by extension. Palaeostress and magma pressure measurement of the G_3 granite confirms such extensional setting during brittle deformation. In addition, strike slip faults and normal faults develop in the extensional setting. Hence, it is interpreted that exhumation through the brittle crust was due to the NW–SE extension. The orogenic trend of the ADMB is NE–SW which was produced from the NW–SE compression. The extension during brittle deformation was NW–SE that was nearly at a right angle to the orogenic trend. Probably, at the end of compressional tectonics, the orogen went through stress relaxation in the same direction as the compression-producing extension.

Extensional tectonics in the Ambaji granulite has been studied for the first time. More work on extensional tectonics is yet to be done in the ADMB. Several basement rocks are exposed in Beawar and further north, which need investigation in light of extensional tectonics. Multiple phases of granite within SDT may be due to extension-induced decompression melting. A preliminary study mentions that the adjoining

Sirohi terrane had experienced a Neoproterozoic extension (Sharma 2005) that created the N–S fractures and ca. 750 Ma Malani igneous suite intruded along such fractures. Sindreh and Punagarh volcano-sedimentary basins were created in the extensional fault-bounded grabens (figure 1b; Bhardwaj and Biswal 2018). Decompression melting induced by such extension probably gave rise to the Malani igneous suite (Eby and Kochhar 1990; Maheshwari *et al.* 2001; Wang *et al.* 2017). The G₃ granite could be due to the decompression melting induced by extension (e.g., Auzanneau *et al.* 2006).

As far as global correlation is concerned, ADMB is shown to be connected to other parts of the Gondwanaland Supercontinent (Singh *et al.* 2010). For instance, the East African orogen, Seychelles, Madagascar and the Arabian–Nubian shield were in continuity with the ADMB. These continents had experienced ca. 750 Ma old magmatism (Tucker *et al.* 1999; Torsvik *et al.* 2001; Ashwal *et al.* 2002; Jöns *et al.* 2006; Biswal *et al.* 2007; Thomas *et al.* 2009; Singh *et al.* 2010 and references therein). Hence, it is likely that Neoproterozoic extensional tectonics was common to all these continents.

6. Conclusions

The Ambaji granulite represents an exhumed middle–lower crustal metamorphic complex within the low–medium grade SDT. The exhumation/uplift of the granulite was a two-stage process: in the first stage, it was exhumed to the BDT zone by thrusting. In the second stage, it was exhumed to the surface by extension. The second stage of exhumation was due to the extension which is well represented by normal faults and G₃ granite veins. From the palaeostress analysis of the ca. 759 Ma G₃ granite veins, a NW–SE extension was interpreted which matches with that of the brittle faults in the area. This suggests that the ADMB crust was stretched in the NW–SE direction right angle to the orogen-length that probably led to the exhumation of the granulite to the surface. Extensional tectonics was probably operative during this period in other continents, namely, the East African orogen, Seychelles, Madagascar and the Arabian–Nubian shield in Gondwanaland, which were in continuity with the ADMB during the Neoproterozoic period.

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