Department of Geological Sciences
Jadavpur University
Kolkata 700032
India

Dr. Tridib Kumar Mondal
Assistant Professor
Tel: (Office) +91 033 2457 2553
Fax: +91 033 2457 2719
e-mail: tridibkumarmondal@gmail.com

April 22, 2020

To
Prof. Soliva Roger
The guest editor
Special Issue in Solid Earth

Subject: Submission of the REVISED MANUSCRIPT for the Special Issue in Solid Earth entitled "Faults, fractures, and fluid flow in the shallow crust".

Dear Editor,

We are grateful to you as well as Prof. Francesco Mazzarini (Reviewer#1) and Prof. Christophe Pascal (Reviewer#2) for a detailed review and constructive suggestions on the manuscript **se-2020-30**, and for giving us an opportunity to revise the same. We believe that the comments have helped us to think more deeply and have helped in revising the manuscript considerably, which we hope will be to your satisfaction. ***In the revised manuscript, we have taken into account all the recommendations/suggestions provided by the two Reviewers and have tried to clarify our viewpoint for the benefit of the reader.***

Please note that in the marked (revised) manuscript, the changes made on basis of comments of Reviewer#1 appear in **RED**, while changes based on comments of Reviewer#2 appear in **BLUE** color.

At first we outlined the main issues that we have addressed in the revision, followed by comment wise response to the specific points mentioned in the comments section. It may be noted that we have also responded the comments of Reviewer#1 and Reviewer#2 separately, below, after the section "response to Editor".

Response to the editor

Response to main issues:

Issue 1: Better justification of considering BTS and minimum principal stress

We would like to thank you as well as reviewer#2 for raising this issue. The tensile strength of metabasalt was obtained from **Brazilian Tensile Strength (**BTS) studies which was further used to denote the magnitude of the minimum principle stress (σ_3). Here we explain the rationale behind this assumption. It is interpreted that the tectonic stress was more dominant during the initial fracturing mechanism which was followed by episodic fluid pressure pulses leading to fracture reactivation and vein emplacement. The 3D Mohr circle diagrams in Fig.7 and Fig.8 (of the revised manuscript), represents the relative fluid pressure conditions only. We have provided the effective normal stress conditions separately in Fig. 11 (Schematic model in the revised manuscript). However, in order to address the Reviewers concern for σ_3=12 MPa, we have added a few sentences in the main manuscript justifying the reason behind such a consideration. It definitely enhanced the quality of the manuscript. The magnitude of σ_3 can also be estimated using the stress intensity factor (fracture toughness), K_{IC}. K_{IC}

for mode-I fractures, can be determined using the following equation (Lawn and Wilshaw, 1975; Atikinson, 1989).

$$K_{IC} = \sigma_3 Y(\pi a)^{1/2},$$

where σ_3 is the minimum far field stress acting normal to the crack, Y is a numerical modification factor to account for the crack geometry and edge effect, and 'a' is the crack half-length. Microstructural investigation suggests that the metabasalts are generally fine to medium grained, massive and consists of plagioclase laths and altered pyroxene with minor chlorite, ankerite and quartz (Gupta et al., 2014). Within the metabasalts, variably oriented larger phenocryst grains range from 2 mm to 8 mm in length. It is evident that the large phenocrysts were more susceptible to generate the initial fractures as compared to the medium to fine grained groundmass in these types of rocks. Therefore, we have considered that the length of the initial crack ranges from 2 mm to 8 mm (Brace, 1964). K_{IC} value for the metabasalts are found to be 1.069 (Donovan, 2003). Considering this K_{IC} value and the range for fracture half-length (a), the $\sigma_3 Y$ value for the metabasalt ranges between 9-19 MPa. From this strength range we considered that 12 MPa is a reasonable estimate for the in situ tensile strength (similar to the laboratory strength) of the corresponding lithology. It may also be noted that, previous studies by Mondal and Acharyya, 2018, conducted in Chitradurga Granite, in close vicinity of the study area also regarded the magnitude of $\sigma_3 \sim 10$ MPa, to be a good estimation. Combining these estimations with the results obtained from the present studies, we constrained the value for $\sigma_3 \sim 12$ MPa.

Issue 2: Estimation of P_f condition

You have raised your concern regarding the estimation of P_f condition, which was also raised by the Reviewer#2. We would again thank the Reviewer for pointing out this problem. In Fig.7, we tried to quantify multiple fluid pressure pulses from the vein pole distribution data. Although, it is critical to differentiate various episodes of fluid ingression from a single large event. Initially we considered the girdle distribution of data points indicating, $P_f > \sigma_2$ (Jolly and Sanderson, 1997; McKeagney et al., 2004; Mazzarini and Isola, 2007; Martinez-Poza et al., 2016). However, as the distribution of data points show three prominent clusters, we decided to extend our analysis to all the respective clusters and not only the WSW cluster (with highest cluster density). We have incorporated the analysis for the other two clusters as well (NE and SE clusters) in the revised manuscript, as also suggested by Reviewer-1 (see Fig. 8 in the revised manuscript). The number of obtained clusters can also be testified through mixed Bingham analysis using K vs BIC (i.e., the number of Bingham component of a mixed Bingham distribution vs Bayesian information criterion; Yamaji and Sato, 2011). We have found that the lowest BIC values are obtained when K=3 (number of possible clusters for the given data set), thereby, justifying the selection of the three clusters for the analysis. In each case, P_f values for the respective clusters were obtained, which is most likely to differ, as mentioned by the Reviewer. It is absolutely true that if we select a tighter cluster, thereby reducing the contour interval, the P_f value will be further reduced. However, field evidences suggest that most of the vein orientations representing the WSW cluster show a NW-SE to NNW-SSE trend. Also, veins along this orientation attained maximum thickness along with multiple median lines. Thus, we decided to extend the contour interval beyond the data points in order to incorporate the maximum range of vein orientations (θ) lying parallel/sub-parallel to the internal anisotropy (as evident from the anisotropy of magnetic susceptibility study) of the host rock. Also, the contour interval and significance level for each of the clusters were selected in such a way that maximum number of data points are included, in order to obtain a statistically viable data cluster. It is however difficult to quantify the lowest P_f value; we therefore intend to use the obtained P_f values from

the respective clusters as examples of low P_f conditions denoting P_f fluctuation rather than quantifying the lowest P_f condition of the study area. We have obtained different shape values (ϕ) for the inversions, this is because of the variation in the magnitude of σ_2. Both magnitude and orientation of σ_2 changes from high to low P_f conditions as explained by the k_2/k_1 ratio, regarded as the stress ratio (ϕ), which is expressed as $k_1 \approx k_2$, for clustered distribution and $k_1 \ll k_2$, for girdle distribution (k_1, k_2 are the concentration parameters of a Bingham distribution; Yamaji, 2016). We hope this provides a better explanation for the interpretation of episodic fluid pressure condition prevailing in the region. In the revised manuscript we have added a number of lines in section 4.3, which increases the clarity of the manuscript.

You have also suggested to include the new figure of the first revision (in accordance with reviewer#1) into the manuscript. In the revised manuscript we have incorporated all the new figures related to the first revision.

Issue 3: Fault valve.
You have mentioned that " I consider your revision, especially the new photograph suggesting crack seal with two episodes. Please, better introduce and discuss the new proofs of fault valve mechanism both in the introduction and your result section. Also include the photographs into the new version of the manuscript (not as a supplementary material) and if possible, replace the close view with another photograph showing better evidences of more cycles into a same vein (here we can really see two episodes). It could be more convincing for the fault valve behaviour. I think to see more convincing cases with multiple adjacent branches in the part (a) of you new figure"

We would like to thank you for your kind words related to the first revision.
We have included a few lines justifying the fault-valve mechanism both in the introduction and in the result section as you have suggested. We have also included the photographs into the main manuscript. We appended Figure 3g, with multiple median lines, where more than two cycles of fluid ingression are observed.

Response to the specific points:
Revise the sense of shear marked with all the arrows in the 3 bloc diagrams of Figure 10b, c and d, which are kinematically inconsistent with the wing cracks drawn. Also better align the yellow arrow with the T criteria in the riedel plane analysis. **CORRECTED**

Provide more justification in the discussion about the deformation mechanism related to the magnetic fabric. Can we interpret the magnetic fabric as non-coaxial (simple shear) or multi episodic deformation (2 poles on the stereogram), and then having a shortening oblique to the foliation ? **CORRECTED and INCORPORATED the suggestion**

Apart from the above we have also modified the manuscript in accordance with the comments mentioned in the annotated pdf.

With the above revisions we hope that all the questions raised by the Reviewers have been addressed. We hope the revised version is to your satisfaction.

Thanking you
Yours sincerely
Tridib Kumar Mondal
(Corresponding author)

Response to Reviewer#1 (Prof. Francesco Mazzarini**)**

We thank Prof. Francesco Mazzarini for his extensive review, and many constructive comments. Although it is suggested for a moderate revision, we believe that the comments have made us to think more deeply and have helped in revising the manuscript considerably. We have implemented, most of the changes suggested and addressed some of his points in details, below. In other cases, we clarified our arguments. It may be noted that the changes are marked in RED color.

Response to main Issues

Issue-1: *Fault-valve action.*
The reviewer has raised his first concern on *fault-valve* action and commented "*Fault valving: the authors propose that fault valving was the driving mechanism to pump fluids. I think this may be possible but both "fragments of host rock" occurrence within veins and mutually cross-cutting relationships are not exclusively indications of fault-valving. These may also indicate a very high fluid pressure surge and "hydrofracturing" of the host rock (fragments) and coeval emplacement of all the veins (mutual crosscutting veins). Probably a fabric analysis of vein may disentangle this point, the occurrence of crack and seal textures in the veins may clearly indicate cyclic fluid ingressions and fault valve mechanism.*"

Yes, we do agree with the reviewer that the presence of host rock fragments in quartz veins and mutually cross-cutting relationships does not exclusively indicate *fault-valve* action. Therefore, as suggested by the Reviewer, in the revised manuscript we have incorporated a new figure 3g, consisting field photographs of metabasalt hosting quartz veins with multiple median lines. This exemplifies crack seal texture in the veins, thereby clearly indicating cyclic fluid ingression and *fault-valve* action that led to the formation of veins in the metabasalts of the Chitradurga region.

Issue-2: *Cluster analysis*
The reviewer has pointed out a number of clustering of veins in the lower hemisphere equal area projection and mentioned that "*In analysing the veins distribution the authors define a clear vein cluster (NNW-SSE veins). If the Jolly and Sanderson method is applied to a cluster of vein clearly it will indicate a cluster distribution. So it is not possible to differentiate different episodes of fluid injection from a large single event where most of the fluid injected the well-oriented NNW-SSE trend- ing fractures (they attain also the maximum vein thicknesses) and also reactivated the other fractures. Moreover, other clusters are apparent in the distribution (for example that around the s2 pole). I suggest to expand the cluster analysis of the data sets and to apply the Jolly and Sanderson method to all the clusters and also to the data set minus the NNW-SSE cluster.*"

Yes, there are a number of clusters, however the WSW cluster is quite prominent with a very high cluster density as compared to the rest. This was the motivation behind primarily considering the WSW cluster for analyzing the fluid pressure condition. Although, it is critical to differentiate various episodes of fluid ingression from a single large event. Therefore, in accordance with the suggestion made by the reviewer we have expanded the analysis and incorporated the other clusters (such as the NE and the SE clusters) in the lower hemisphere equal area projection of pole to veins. The figure 8, provides all the cluster analysis in this regard. In the revised manuscript we have incorporated the same and changes have been made accordingly which definitely increases the clarity of the manuscript.

Response to minor comments

Apart from the above comments the Reviewer has commented few more in the specific line positions of the manuscript, which are listed below.

Lines 47-48. *This is not completely true. Fault valve action develops when fluid pressure shows a cyclic increase. All veins forms because of dilation of fracture's walls. Please reword the sentence.*

Reply: We have reframed the entire sentence in the revised manuscript as suggested by the Reviewer.

Lines 55-58. *not clear, please reword.*

Reply: The sentences have been reframed in the revised manuscript.

Line 124. *angular enclaves suggest high fluid pressure at the time of vein formation with rupture of wall rocks (hydrofracture). Fault valving is testified by crack and seal fabric of veins. The occurrence of striated veins suggests active stress field after the vein formation.*

Reply: This is one of the major issues suggested by the Reviewer. This has been previously addressed in Issue-1: Fault-valve action, and accordingly a new figure 3g has been added with the main manuscript as a response to the comment. The process of fracturing, fracture reactivation/faulting along with vein emplacement prevailed in an active stress field as pointed out by the Reviewer.

Lines 147-148. *this is not clear. Why mutually cross-cutting relationships do imply several cycles of emplacement? It is possible that this pattern of veins indicates a coeval formation of veins?*

Reply: At high fluid pressure condition (supra-lithostatic levels), P_f exceeds the stresses acting on the fracture/fault plane, thus causing failure and forming mesh of fractures. Subsequently, the fluid flows into this mesh of fractures, a phenomenon analogous to "*burping*" (Sibson and Scott, 1998), and the fluid pressure drops. The veins seal the fractures/faults, and the system is once again ready for the next cycle of fluid pressure build-up, failure, fluid flow (*burping*) and subsequent vein formation. This phenomenon involving repeated cycles leads to crosscutting veins and fractures (mesh-like structure; Mondal and Mamtani, 2013; Sibson, 2004 and the references therein). Under successive low P_f conditions, the orientations represented by the individual clusters (WSW, NE and SE) were reactivated selectively depending on their respective orientation to the tectonic stress field and the fluid pressure magnitude.

Lines 256-259. *This is an important point. Looking at the veins' pole distribution also a cluster around the intermediate stress (s2) is apparent. Construction of data set from clustered data clearly will lead to a cluster distribution. I suggest here to provide a clear cluster analysis of the data and to extend the analysis to all the resulting clusters. Once these results are obtained, the question to face is: are these different pluses of fluid injections? Is clustering inherited by the fracture network exploited by fluids?*

Reply: All the respective clusters have been separately evaluated as suggested by the Reviewer (Fig. 8). Fluid pressure conditions (P_f) are determined discretely for each of these clusters. The variation in P_f clearly indicates the existence of different pulses of fluid injection. All such orientations represented in the cluster have been exploited by fluids as evident from vein emplacement along these orientations. However, the maximum vein thickness is recorded along NNW-SSE direction.

Lines 348-356. *These sentences are repetitive. You may expand the geological back- ground and cut off here these sentences.*

Reply: The sentences that are repetitive have been omitted as suggested by the Reviewer.

Line 387. *This is ok from a tectonic point of view. Now rocks are exposed. When did rocks' exposure occur? Unloading form a few kilometres to the surface did not generate any jointing? This point here should be discussed.*

Reply: The host metabasalts of the study area have an island arc affinity (Chakrabarti et al., 2006) and can be related to the accretion of EDC (Eastern Dharwar craton) and WDC (Western Dharwar craton) along the CSZ (Chitradurga Shear Zone). Unloading from a few kilometers to the surface might generate jointing in host rocks, however, we did not find any such field evidence to support this.

Line 427. *please expand this point to clearly state that these fracture systems are coeval.*

Reply: Necessary change has been made in the manuscript as suggested by the Reviewer.

Line 470. *as in the above comment. How do you ascribe to vein formation the cluster? The cluster my be inherited by the existing fracture network at the time of vein emplacement.*

Reply: We have separately analyzed each of the clusters as suggested by the Reviewer. In each case the respective fluid pressure conditions (P_f) have been evaluated. The WSW (highest density cluster, Fig. 7c) ascribes to the NNW-SSE trending vein orientations (attaining the maximum thickness). The NE and the SE clusters (Fig. 8) can be related to the vein orientations emplaced along the R and X shear fractures respectively (see figure 11 of the revised manuscript).

Lines 474-476. *As discussed above. Angular fragments of hosting rock within veins indicate hydrofracture with rupture of wall rocks. This is not directly associated with fault-valve action. Moreover, it is not clear if indications of hydrofracturing are observed in all vein sets or only in the NNW-SSE set. To clearly define a fault-valve action a look at the vein microfabric (crack and seal textures) will help.*

Reply: This point has been addressed in Issue-1 (response to the main issues) discussed above.

Figure 1. *Add definition of TTG and Supracrustals in the key legend.* Figure 6. *label (c) is poorly visible.* Figure 10. *The stress field in (c) has s1 vertical while the cartoon has ESE-WNW contraction (yellow arrows). If fluid overpressure acted this should put into the figure caption.*

Reply: All the suggested corrections in Figures. 1, 6 and 10 have been incorporated in the main manuscript.

Apart from the above, the reviewer suggested a few minor corrections in the annotated manuscript (pdf), which has been addressed in the revised manuscript.

Response to Reviewer#2 (Prof. Christophe Pascal)

We thank the Prof. Christophe Pascal for the valuable and constructive comments on the manuscript. The comments have made us think more deeply and have helped in revising the manuscript considerably. The reviewer has mentioned two issues regarding the manuscript. It may be noted that the changes are made in BLUE color

Issue: 1

The reviewer has raised his first concern regarding the quantification of sigma 3 and mentioned "*In page 14 (lines 273-274), it is mentioned: "Tensile strength of metabasalt (_12 MPa; obtained from BTS studies) indicates that the minimum principal stress (sigma3) has to be sigma3 _ 12 MPa." Thereafter, this value is selected as magnitude for the minimum principal stress for the stress reconstructions (e.g. Fig. 7). I am particularly puzzled by the reasoning. The condition for tensile fracturing is sigma3 – pore pressure less or equal to the negative value of tensile strength. That is if sigma3 = 12 MPa then P_f has to be equal or higher than 24 MPa... Starting from there could the authors explain how they constrain sigma3?*"

Reply:

We would like to thank the reviewer for addressing this issue. The tensile strength of metabasalt was obtained from BTS studies which was further used to denote the magnitude of the minimum principle stress (σ_3). Here we explain the rationale behind this assumption. It is interpreted that the tectonic stress was more dominant during the initial fracturing, which was followed by episodic fluid pressure pulses leading to fracture reactivation and vein emplacement. The 3D Mohr circle diagrams in Fig.7 and Fig.8 (of the revised manuscript), represents the relative fluid pressure conditions only. We have provided the effective normal stress conditions separately in Fig. 11 (Schematic model in the revised manuscript). However, in order to address the Reviewers concern for σ_3=12 MPa, we have added a few sentences in the main manuscript justifying the reason behind such a consideration. It definitely enhanced the quality of the manuscript. The magnitude of σ_3 can also be estimated using the stress intensity factor (fracture toughness), K_{IC}. K_{IC} for mode-I fractures, can be determined using the following equation (Lawn and Wilshaw, 1975; Atikinson, 1989).

$K_{IC} = \sigma_3 Y(\pi a)^{1/2}$,

where σ_3 is the minimum far field stress acting normal to the crack, Y is a numerical modification factor to account for the crack geometry and edge effect, and 'a' is the crack half-length. Microstructural investigation suggests that the metabasalts are generally fine to medium grained, massive and consists of plagioclase laths and altered pyroxene with minor chlorite, ankerite and quartz (Gupta et al., 2014). Within the metabasalts, variably oriented larger phenocryst grains range from 2 mm to 8 mm in length. It is evident that the large phenocrysts were more susceptible to generate the initial fractures as compared to the medium to fine grained groundmass in these types of rocks. Therefore, we have considered that the length of the initial crack ranges from 2 mm to 8 mm (Brace, 1964). K_{IC} value for the metabasalts are found to be 1.069 (Donovan, 2003). Considering this K_{IC} value and the range for fracture half-length (a), the $\sigma_3 Y$ value for the metabasalt ranges between 9-19 MPa. From this strength range we considered that 12 MPa is a reasonable estimate for the in situ tensile strength (similar to the laboratory strength) of the corresponding lithology. It may also be noted that, previous studies by Mondal and Acharyya, 2018, conducted in Chitradurga Granite, in close vicinity of the study area also regarded the magnitude of $\sigma_3\sim$10 MPa, to be a good estimation. Combining these estimations with the results obtained from the present studies, we constrained the value for $\sigma_3 \sim$12MPa.

Issue: 2

The reviewer has raised his second concern regarding the Pf condition and mentioned *"It is proposed that the veins formed in response to various fluid pressure pulses (see pages 13 and 14, and Fig. 7), which is reasonable and supported by numerous studies (e.g. discussion in Yamaji et al. 2010, p. 1139). The analysis suggests two extreme values for the fluid pressure: a maximum Pf derived from the Bingham distribution of all the measured veins and a minimum Pf, corresponding to the Bingham distribution of a selected subset of veins forming an elliptical cluster around sigma3 (see Fig. 7). It is totally unclear how the authors have selected the subset indicating, presumably, the actual minimum pore pressure. For example if one decides to select another subset of poles forming a tighter cluster around sigma3, Pf will be further reduced. It is just a mathematical consequence (see Jolly and Sanderson 1997)... In addition, stress anisotropy is theoretically insensitive to pore pressure variations. Surprisingly, the two inversions shown in Fig. 7 indicate rather different shape values, though pore pressure is the only quantity that is expected to change. In conclusion, the results themselves suggest that the selection of the subset of poles is merely subjective and the advanced minimum pore pressure value badly supported by the analysis".*

Reply:

We would again thank the Reviewer for pointing out this problem. In Fig.7, we tried to quantify multiple fluid pressure pulses from the vein pole distribution data. Although, it is critical to differentiate various episodes of fluid ingression from a single large event. Initially we considered the girdle distribution of data points indicating, $P_f > \sigma_2$ (Jolly and Sanderson, 1997; McKeagney et al., 2004; Mazzarini and Isola, 2007; Martinez-Poza et al., 2016). However, as the distribution of data points show three prominent clusters, we decided to extend our analysis to all the respective clusters and not only the WSW cluster (with highest cluster density). We have incorporated the analysis for the other two clusters as well (NE and SE clusters) in the revised manuscript, as also suggested by Reviewer-1 (see fig. 8 in the revised manuscript). The number of obtained clusters can also be testified through mixed Bingham analysis using K vs BIC (i.e., the number of Bingham component of a mixed Bingham distribution vs Bayesian information criterion; Yamaji and Sato, 2011). We have found that the lowest BIC values are obtained when K=3 (number of possible clusters for the given data set), thereby, justifying the selection of the three clusters for the analysis. In each case, P_f values for the respective clusters were obtained, which is most likely to differ, as mentioned by the Reviewer. It is absolutely true that if we select a tighter cluster, thereby reducing the contour interval, the P_f value will be further reduced. However, field evidences suggest that most of the vein orientations representing the WSW cluster show a NW-SE to NNW-SSE trend. Also, veins along this orientation attained maximum thickness along with multiple median lines. Thus, we decided to extend the contour interval beyond the data points in order to incorporate the maximum range of vein orientations (θ) lying parallel/sub-parallel to the internal anisotropy (as evident from the anisotropy of magnetic susceptibility study) of the host rock. Also, the contour interval and significance level for each of the clusters were selected in such a way that maximum number of data points are included, in order to obtain a statistically viable data cluster. It is however difficult to quantify the lowest P_f value; we therefore intend to use the obtained P_f values from the respective clusters as examples of low P_f conditions denoting P_f fluctuation rather than quantifying the lowest P_f condition of the study area. We have obtained different shape values (ϕ) for the inversions, this is because of the

variation in the magnitude of σ_2. Both magnitude and orientation of σ_2 changes from high to low P_f conditions as explained by the k_2/k_1 ratio, regarded as the stress ratio (ϕ), which is expressed as $k_1 \approx k_2$, for clustered distribution and $k_1 << k_2$, for girdle distribution (k_1, k_2 are the concentration parameters of a Bingham distribution; Yamaji, 2016). We hope this provides a better explanation for the interpretation of episodic fluid pressure condition prevailing in the region. In the revised manuscript we have added a number of lines in section 4.3, which increases the clarity of the manuscript.

With the above revisions I hope that all the questions raised by the Reviewer #2 has been addressed.

Control of pre-existing fabric in fracture formation, reactivation and vein emplacement under variable fluid pressure conditions: An example from Archean Greenstone belt, India.

Sreyashi Bhowmick and Tridib Kumar Mondal

Department of Geological Sciences, Jadavpur University

5 Kolkata-700032, West Bengal, India

*Corresponding author: **Tridib Kumar Mondal (tridibkumarmondal@gmail.com)**

Alternate E-mail: **tridibk.mondal@jadavpuruniversity.in**

Abstract

10 Most of the upper crustal fluid flows are strongly influenced by the pre-existing fractures/foliations in the

rocks under a certain state of tectonic stress and fluid pressure condition. In the present study, we analysed

a wide range of crosscutting fractures that are filled with quartz veins of variable orientations and

thicknesses, from the gold bearing massive metabasalts (supracrustal) of the Chitradurga Schist Belt

adjacent to the Chitradurga Shear Zone (CSZ), western Dharwar craton, south India. The study involves

15 the following steps: 1) analysing the internal magnetic fabric using anisotropy of magnetic susceptibility

(AMS) studies, and strength of the host metabasalts, 2) quantifying the fluid pressure condition through

lower hemisphere equal area projection of pole to veins by determining the driving pressure ratio (R′),

stress ratio (ϕ), and susceptibility to fracturing, and 3) deciphering the paleostress condition using fault

slip analysis. We interpret that the NNW-SSE to NW-SE (mean 337 º/69º NE) oriented magnetic fabric

20 in the rocks of the region developed during regional D1/D2 deformation on account of NE-SW shortening.

However, D3 deformation manifested by NW-SE to E-W shortening led to the sinistral movement along

CSZ. As a consequence of this sinistral shearing, fractures with prominent orientations formed riedel shear components, with CSZ as the shear boundary. Subsequently, all the pre-existing fabrics along with the riedel shear components were reactivated and vein emplacement took place through episodic fluid pressure fluctuation from high to low P_f at shallow depth (~2.4 Km). However, NNW-SSE orientations were susceptible to reactivate under both high and low P_f conditions thereby attaining maximum vein thickness along these orientations. The deduced paleostress from fault-slip analysis, along with the kinematics of the fractures and veins are in good agreement with previously estimated regional tectonics. Thus, integrating multiple domains of studies, help in the logical interpretation of fluid flow condition and vein emplacement mechanism in the study area that has not been ventured before.

1. Introduction

The upper crust is replete with fractures/faults, which act as pathways for fluid flow and vein emplacement. Fracture formation and vein emplacement mechanisms are closely interrelated, and require a detailed study for finding out potential hydrothermal deposits. Fracture formation and reactivation involves a combination of regional stress field (far field stress), stress ratio (Φ) and driving pressure ratio (R´) that helps to determine the prevailing fluid pressure condition (Delaney et al., 1986; Jolly and Sanderson, 1997; McKeagney et al., 2004; Mazzarini and Isola, 2007; Martinez-Poza et al., 2016; Cucci et al., 2017). However, previous studies suggest that pre-existing anisotropy in host rocks play a significant role in formation and propagation of fractures provided the anisotropy is favorably oriented to the far field stresses (Ikari et al., 2015; Donath, 1961; Hoek, 1964; Attwell and Sandford, 1974). Presence

of such favorably oriented anisotropy lowers the shear strength of the host rocks, enabling failure/slip along them at minimum compressive stress, prior to/during vein emplacement. Such conduits are reactivated at both high and low fluid pressures forming pathways for fluid flow (Mondal and Mamtani

45 2013, Lahiri and Mamtani, 2016). Thus, vein emplacement mechanism requires favorably oriented fractures that can be reactivated, when fluid pressure gradually builds and exceeds the normal stresses acting on the fracture wall (Gudmundsson, 2011). This enables the fractures to open up, under cyclic increase of fluid pressure along such pre-existing conduits, a mechanism known as *fault-valve action* (Sibson et al., 1988; Sibson, 1992, 1996, 2000; Boullier and Robert, 1992; Sibson and Scott, 1998; Petit

50 et al., 1999; Cox et al., 2001 among others). Subsequently, fluid flows into the fractures, a phenomenon analogous to *burping*, triggering an immediate drop in fluid pressure. This sudden drop in fluid pressure is responsible for mineral deposition and vein formation (Cox et al., 1991, Cox, 1995; 2001). Vein materials thus deposited seals the fracture/fault planes, preparing the system for the next cycle of fluid pressure build up, rupture, fluid flow and vein formation (Mondal and Mamtani, 2013; Lahiri and

55 Mamtani, 2016; Marchesini et al., 2019). Thus, repeated cycles of elevated and depleted fluid pressure generate widespread networking of veins in host rocks. Studies conducted in this approach help to understand the mechanism of fabric development and fracture formation vis-à-vis vein emplacement. This study also aims to provide a detailed insight about the development of brittle structures and their role in understanding the tectonic evolution of Archean cratons.

60 The Chitradurga Schist belt (western Dharwar craton, south India), is a NW-SE trending Archean greenstone belt, known to harbor a widespread network of veins with potential epigenetic gold bearing lodes (Gupta et al., 2014; Gopalakrishna et al., 2018). We have conducted this study in the meta-volcanic

(metabasalt), hosting quartz veins of variable orientations and thicknesses, in and around Chitradurga region. We emphasize on understanding the mechanism of vein emplacement under a tectonic environment where propensity of fracture reactivation for vein emplacement is mutually dependent on both fluid pressure condition and the regional far field stresses. The present paper is a comprehensive work which quantifies the fabric in the visually isotropic metabasalts of the Chitradurga Greenstone belt and its role in fracture formation and in channelizing upper crustal fluids. We also found the potential reactivation ability of the fractures/faults at variable fluid pressure conditions to investigate the role of fractures/faults which are not favorably oriented to the pre-existing anisotropy and regional stress field, and their contribution for vein emplacement in the study area.

2. Geology of the study area

The study has been conducted in the Chitradurga Greenstone Belt of Dharwar craton (southern India; Fig. 1a), which represents a complex geological history. Dharwar craton exposes >3.0 Ga, Archean continental crusts, represented by the TTG (trondjemite-tonalite-granodiorite gneiss) also known as the peninsular gneiss (Jayananda et al., 2006). The craton stabilized during the accretion of Eastern Dharwar Craton (EDC) and Western Dharwar Craton (WDC) at 2.75-2.51 Ga. The zone of accretion of the two tectonic blocks is marked by a shear zone, referred to as Chitradurga Shear Zone (e.g., Naqvi and Rogers, 1987; Chadwick et al., 2003; Jayananda et al. 2006). The eastern part of WDC marked by Chitradurga Schist Belt (CSB) (Fig. 1b), comprises of peninsular gneiss (3.4-3.0 Ga), and younger supracrustal rocks (Beckinsale et al., 1980; Sarma et al., 2011; Taylor et al., 1984). The latter comprises metavolcanics/metabasalts (greenstone belt; greenschist/lower amphibolite facies metamorphism),

metamorphosed greywacke-argillite (interbanded with ferruginous chert and banded iron formation),

85 polymict conglomerate, and ferruginous chert. The basaltic rocks of the schist belt have an island arc affinity (Chakrabarti et al., 2006). Regionally, the belt is surrounded by older peninsular gneisses and younger granitoids (Ramakrishna and Vaidyanadhan, 2010). Previous geological investigations, revealed the presence of various younger granites ~2.6 Ga; (Jayananda et al., 2006; Chardon et al., 2002) which are associated with the schist belt, such as Chitradurga granite, J. N. Kote granite. The structural

90 investigations of the adjacent meta-sedimentary rocks of the region show that the area has undergone three phases of deformation: D1, D2 and D3 respectively (Chadwick et al., 1989; Jayananda et al., 2006; Mondal and Mamtani, 2014).The D1/D2 deformations are coaxial with NW-SE striking axial plane. D1 folds are tight to isoclinal and asymmetric while the D2 folds are open to tight and upright. Earlier studies revealed that the folds (regional open; NE-SW striking vertical axial plane), related to early D3

95 deformation superposed the D1/D2 structures thus resulting in dome-basin geometry in the meta-sedimentary rocks of that region (Chakrabarti et al., 2006; Mondal and Mamtani, 2014). However, later phase of D3 deformation led to the formation of brittle structures in the younger granites of CSB (Mondal and Mamtani, 2016). The NE-SW shortening during D1/D2 deformation was responsible for NW-SE oriented structural elements in the CSB (Chadwick et al., 2003), while NW-SE to E-W shortening

100 direction prevailed during D3 deformation (Jayananda et al., 2006; Mondal, 2018; Mondal and Acharyya, 2018). A number of petrological and geochemical investigations have been carried out on the area in the past. These studies suggest the presence of actinolite, albite, chlorite, epidote, quartz and calcite in the basaltic rocks (Chakrabarti et al., 2006). The CSB holds evidence of progressive metamorphism with a gradual increase in P-T conditions (approximately 3-4 Kb of pressure), from greenschist facies in the

north to amphibolite facies in the south suggesting the depth of deformation to be 10-12 Km (during D1/D2). However, recent studies by Acharyya and Mondal, (2019) shows that the brittle deformation during late D3 took place at a shallow depth of ~2-4 km. The dashed rectangular area in figure 1b demarcates the study area. The present study focuses on the dark greyish to blackish, massive to fine grained, altered metabasalt hosting quartz veins, of the region surrounded by meta-sedimentary sequences (Fig. 2). The metabasalts of the study area are devoid of any well-defined mesoscopic foliation. The foliation planes in the adjacent meta-sedimentary rocks of the region are found to be NW-SE oriented (mean strike/dip is 323º/71º NE). Since, the metabasalts are devoid of mesoscopic field fabric, the anisotropy of magnetic susceptibility (AMS) study has been conducted in order to quantify their internal magnetic fabric.

3. Overview of brittle structures

Metabasalts of the study area are replete with fractures and faults of multiple orientations. Some of these fractures and faults are found to host quartz veins forming criss-cross pattern (Fig. 3a and c) and some of them are devoid of any vein material. Growth of vein materials (quartz crystals) are often found to be perpendicular to the vein wall suggesting that dilation was significant in these veins (Fig.3b). The maximum width and length of the quartz veins are ~1 meter and ~130 meters respectively. Some of the quartz veins are found to be displaced by other ones forming crisscross network of veins in the study area (Fig. 3c). Wing cracks filled up with quartz veins are also observed (Fig. 3d). At few places, the thicker quartz veins show series of successive fault planes with slickenside lineations on them (Fig. 3e and *in-set*). Those veins are often found to enclose angular metabasalt enclaves (host material, Fig. 3f),

suggesting that fault valve action was predominant in the region. Quartz veins are recorded with multiple median lines as an evidence of crack-seal mechanism due to cyclic fluid ingression (Fig. 3g). Some of the fault planes recorded in the study area have shallow plunging slickenside lineations while others have moderate to high plunge. Both Left Lateral Faults (LLF's) and Right Lateral Faults (RLF's) are recorded based on the movement of the hanging wall with respect to the footwall. Presence of congruous steps helps in the discrete identification of the fault planes (Fig. 3h). Although, quartz veins of variable orientations and thicknesses are found, however, most of the veins are predominantly NNW-SSE trending (Fig. 4a). Most of the fractures and faults show NNW-SSE trend (maxima) whereas some others form a WNW-ESE to NE-SW sub maxima respectively (Fig. 4b & 4c). Some WNW-ESE trending Mode-I (tensional) cracks with prominent tips are also recorded from the study area which are often filled up with quartz veins. It may be noted that the veins with maximum thicknesses are oriented along NNW-SSE direction (Fig. 4d). In this study, 992 fracture data (strike/dip), 378 vein data (strike, dip and thickness) and 73 fault data (strike, dip and slip) have been measured from the metabasalt exposures at about 13 locations in the entire study area. All 73 shallow to moderately plunging fault planes are used to decipher the paleostress condition. Thus, the strict spatial and temporal relationships between brittle structures and veins provided by field observations help to quantify the fluid pressure conditions that prevailed during fracture reactivation and vein emplacement. It also provides information for reconstructing the tectonic stress conditions of the craton.

4. Methods of analysis and results

The quartz veins have been emplaced in the massive metabasalts of the region that are devoid of any prominent mesoscopic foliation as mentioned above. At places, veins of one orientation are dissected and sometimes displaced by others that led to the formation of mesh like structures (Fig. 3a, c). Sibson (1992) has mentioned that such a mesh is formed when a rock contains fractures of variable orientations that may

150   get reactivated due to rise in fluid pressure. It is mentioned that in the Chitradurga region, veins of various orientations show mutually cross-cutting relationships, which implies repeated cycles of vein emplacement (see section 3; Mondal and Mamtani, 2013; Sibson, 1992). Although veins have various orientations, NNW-SSE striking veins are the most common (Fig. 4a). It may be noted that NW-SE to NNW-SSE direction, which defines the maximum strike orientation of quartz veins, fractures and faults,

155   is also the orientation of the adjacent Chitradurga shear zone, the overall trend of the schist belt. This implies that there is a strong structural control on the formation of these quartz veins. It has been shown earlier that the pre-existing anisotropy plays a critical role in propagating fractures and channelizing fluid in rocks (Sanderson and Zhang, 1999, Cox et al., 2001 and Ikari et al., 2015). It is also known from rock mechanics investigations that the rock strength variation controls the strain partitioning and influences

160   fluid flow (e.g., Tsidzi, 1990; Vishnu et al 2018). Therefore, it is crucial to determine the orientation of anisotropy in host rocks and the state of stresses governing the upper crustal fluid flow vis-à-vis vein emplacement.

3-D Mohr circle analysis has been performed by Jolly and Sanderson (1997) using dyke orientation data to examine the magma pressure condition that was responsible for the opening of pre-existing fractures

165   during dyke emplacement. Further the work has been extended to understand the fluid pressure condition and vein emplacement mechanism by McKeagney et al., 2004 (also see Yamaji et al., 2010).We present

vein orientation data from the Chitradurga region (southern India), which is a province of epigenetic gold deposit (Gupta et al., 2014;Gopalakrishna et al., 2018).

We conduct anisotropy of magnetic susceptibility (AMS) study, followed by Brazilian Tensile strength (BTS) determination in order to quantify the internal magnetic fabric and tensile strength of the rocks within the study area. The 3-D Mohr circle construction using quartz vein orientation data helps to recognise the fluid pressure conditions under which they were emplaced. Further, these fluid pressure conditions were integrated with dilation tendency, slip tendency and fracture susceptibility in order to understand the mechanism of vein emplacement in the Chitradurga region. A combination of data obtained from these methods along with paleostress analysis using fault-slip data recorded from the study area provides a comprehensive evaluation of vein forming conditions in Chitradurga greenstone belt.

4.1 Anisotropy of Magnetic Susceptibility (AMS)

The quartz veins occur in massive metabasalt, which does not show any visible field foliation. However, such visibly massive rocks may preserve an internal fabric, which can be recognized through anisotropy of magnetic susceptibility (AMS) studies (e.g., Tarling and Hrouda, 1993; Maffione et al., 2015; Mamtani and Greiling, 2005; Raposo et al., 2007; Loock et al., 2008; Mondal and Mamtani, 2014; Mondal, 2018). The study involves preparation of cylindrical core samples (25.4 mm diameter × 22 mm height) from oriented metabasalt blocks. These metabasalt block samples have been collected from 13 different locations (Fig. 5) in the study area. The prepared core samples are subjected to an external magnetic field and the induced magnetization for each core sample is measured in different directions. AMS is considered to be a symmetric second-rank tensor, represented by an ellipsoid with three mutually

perpendicular principal axes, K_1, K_2 and K_3 respectively where ($K_1 \geq K_2 \geq K_3$). The orientation and magnitude of each of these principal axes are determined in this analysis, where K_1 represents the magnetic lineation, K_3 is the pole to the magnetic foliation (K_1K_2). Using the magnitudes of K_1, K_2 and K_3, several AMS parameters are calculated such as magnetic susceptibility (K_m), magnitude of the magnetic foliation (F) and magnetic lineation (L), degree of magnetic anisotropy (P_j or P´) and shape parameter (T). The formulae for the parameters are given below (after Tarling and Hrouda, 1993; Jelínek, 1981):

$$K_m = (K_1+K_2+K_3) / 3, \tag{1}$$

$$F = (K_2-K_3) / K_m, \tag{2}$$

$$L = (K_1-K_2) / K_m, \tag{3}$$

$$P_j = \exp \sqrt{\{2 \, [(\eta_1-\eta_m)^2 + (\eta_2-\eta_m)^2 + (\eta_3-\eta_m)^2]\}}, \tag{4}$$

$$T = (2\eta_2-\eta_1-\eta_3) / (\eta_1-\eta_3), \tag{5}$$

Here, $\eta_1 = \ln K_1$, $\eta_2 = \ln K_2$, $\eta_3 = \ln K_3$ and $\eta_m = (\eta_1.\eta_2.\eta_3)^{1/3}$. In the above equations, P_j and T give the measure of the eccentricity and shape of the AMS ellipsoid respectively. The value of T ranges between -1 to +1. Positive and negative values represent oblate and prolate shapes of the AMS ellipsoid (Tarling and Hrouda, 1993).

AMS measurements have been conducted in the spinner mode (field intensity of 300 Am^{-1}) using the KLY-4S Kappabridge (AGICO, Czech Republic); see Hrouda et al. (2006) for instrument details. The SUFAR program has been used to calculate the required AMS parameters described above for each sample. A total of 65 cores are prepared and analysed. The mean value of the AMS parameters at each

location is calculated using the program Anisoft (version 4.2, AGICO; Jelinek statistics, Jelinek, 1981).It

is noted that the K_m varies between 37 and 1280×10^{-6} SI units, with most of the samples having K_m below

210   1000×10^{-6} SI units (see supplementary sheet-1). This indicates that paramagnetic and ferromagnetic

minerals contribute significantly to the AMS. Petrographic studies reveal the presence of actinolite,

hornblende, chlorite, albite, epidote, pyrite which are inferred to contribute to the susceptibilities recorded

in the samples. The P_j lies between 1.003 and 1.539, and the shape of the AMS ellipsoid is dominantly

oblate (positive T values; see supplementary sheet-1). It is noted that the magnetic foliation (K_1K_2 plane)

215   is consistently NW-SE striking (mean orientation: 337º/69º towards NE; Fig. 5a). The magnetic lineations

plunge variably from NNW, through sub-vertical to SSE (Fig. 5b).

4.2 Tensile strength determination

It is known that the dilation occurs in a direction parallel to the minimum compressive principal

220   stress (σ_3), when the fluid pressure (P_f) exceeds the normal stress acting on the fracture wall.

Therefore, the fractures may occur at any depth when the effective stress ($\sigma_3 - P_f$) is sufficient to

counteract the tensile strength (T) of the rocks (Gudmundsson, 2011). We measure the tensile

strength of the host metabasalts to quantify the P_f that prevailed during vein emplacement in the

region. The measurement of direct tensile strength requires machined specimens and also involves

225   difficulty in applying tensile load on the cylindrical specimen during analysis. Therefore, tensile

strength measurement of rocks using Brazilian test has become imperative in rock mechanics.

Compression-induced extensional fractures are generated in the test which essentially involves line-

loading on a circular disk placed between two platens (Aydin and Basu, 2006; Basu et al., 2013; see

Fig.6).This tensile strength (T) is estimated from the elastic theory (ISRM, 1978; ASTM D3967,
230   2001):

$$T = \frac{2P}{\pi LD} \ .$$

(6)

Here, P is peak/failure load, and L and D, are the length and diameter of the disk respectively. For this
analysis, 18 core samples were drilled from metabasalt blocks which were later resized to obtain the
desirable cores for the analysis (length: diameter = 1: 2). The maximum tensile strength of each specimen
235   at the instance of failure is recorded. The maximum tensile strength for 18 samples are averaged out to
obtain the approximate tensile strength of metabasalts, which is ~12 MPa. This tensile strength value is
further used for quantifying the P_f in 3D Mohr circle using vein orientation data.

4.3 Fluid pressure determination

240   Here, we have used the method proposed by Jolly and Sanderson (1997) to quantify the P_f conditions that
led to the vein emplacement in metabasalts of Chitradurga region (southern India). We have used the
lower hemisphere equal area projection of the poles to quartz vein data. According to Jolly and Sanderson
(1997), girdle distribution of vein pole data implies $P_f > \sigma_2$, described as a condition where large number
of fracture orientations are susceptible to reactivate, while $P_f < \sigma_2$, represents clustered distribution of vein
245   pole data, where only limited range of fracture orientations reactivate. Depending on the type of
distribution (girdle/cluster), parameters such as stress ratio (ϕ) and driving pressure ratio (R′) are

calculated using ranges of fracture orientations (θ_1, θ_2 and θ_3) from the following equations provided by Jolly and Sanderson, 1997 and Baer et al., 1994.

$$R' = \frac{P_f - \sigma_3}{\sigma_1 - \sigma_3} = \frac{1 + cos2\theta_2}{2}. \qquad (7)$$

250   For $P_f > \sigma_2$,

$$\Phi = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} = 1 - \frac{1 - cos2\theta_2}{1 - cos2\theta_3}. \qquad (8)$$

For $P_f < \sigma_2$,

$$\Phi = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} = \frac{1 + cos2\theta_2}{1 + cos2\theta_1}. \qquad (9)$$

In figure 7a, the lower hemisphere equal area projection of pole to vein data shows girdle distribution,

255   implying high fluid pressure condition ($P_f > \sigma_2$). From this distribution the orientations of the principal stress axes (σ_1, σ_2 and σ_3) are determined using the Bingham statistics of the Stereonet 9 software (**http://www.geo.cornell.edu/geology/faculty/RWA/programs/stereonet.html**). σ_1 is sub-vertical lying in the empty space devoid of any vein pole data. Subsequently, following Jolly and Sanderson (1997), the planes $\sigma_1\sigma_2$, $\sigma_1\sigma_3$ and $\sigma_2\sigma_3$ are constructed and the range of fracture orientations, θ_2 and θ_3 are determined

260   along the $\sigma_1\sigma_3$ and $\sigma_1\sigma_2$ planes respectively. For this high P_f condition, $\theta_2 = 27°$, $\theta_3 = 59°$ from which $\phi = 0.72$ and $R' = 0.8$ are calculated. Thus, such a P_f condition enhances the chances of vein emplacement along various orientations. Although pole to vein data represents a girdle distribution pattern, however the distribution of the data points shows three prominent clusters. The WSW cluster forms the highest density cluster around the σ_3 axis indicating a number of veins with similar orientations. The cluster

265   primarily represents the NNW-SSE to NW-SE trending veins, attaining the maximum thickness. It is to

be noted that majority of the veins are oriented along this direction (see Fig. 4a), which also suggests that the vein forming fluid must have been channelized through a pre-existing anisotropy (trending NW-SE to NNW-SSE, see section *4.1*). These data are segregated and plotted separately in the lower hemisphere equal area projection and thus the obtained contour defines the WSW cluster (Fig. 7c). We decided to extend the contour interval beyond the data points in order to incorporate the maximum range of vein orientations (θ) lying parallel/sub-parallel to the internal anisotropy (as evident from the anisotropy of magnetic susceptibility study) of the host rock. Also, the contour interval and significance level for each of the clusters were selected in such a way that maximum number of data points are included, in order to obtain a statistically viable data cluster. Apart from the WSW cluster (with a high cluster density), the SE and the NE clusters (with higher data spreading) are also evaluated discretely (Fig. 8). The number of obtained clusters can also be testified through mixed Bingham analysis using **K** vs BIC (i.e., the number of Bingham component of a mixed Bingham distribution vs Bayesian information criterion; Yamaji and Sato, 2011). We have found that the lowest BIC values are obtained when **K**=3 (number of possible clusters for the given data set), thereby, justifying the selection of the three clusters for the analysis. It is however difficult to quantify the lowest P_f value; we therefore intend to use the obtained P_f values from the respective clusters as examples of low P_f conditions denoting P_f fluctuation rather than quantifying the lowest P_f condition of the study area. The orientations of the principal stress axes (σ_1, σ_2 and σ_3) are determined using the Bingham statistics of the Stereonet 9 software. Similarly, the $\sigma_1\sigma_2$, $\sigma_1\sigma_3$ and $\sigma_2\sigma_3$ planes are constructed and the range of fracture orientations θ_1 and θ_2, are calculated along the $\sigma_2\sigma_3$ and $\sigma_1\sigma_3$ planes. Again, for low P_f conditions, $\theta_1 = 38^\circ$, $\theta_2 = 43.2^\circ$, $\phi = 0.85$ and $R' = 0.53$ (WSW cluster, Fig. 7c); $\theta_1 = 32^\circ$, $\theta_2 = 35^\circ$, $\phi = 0.93$ and $R' = 0.67$ (NE cluster, Fig. 8a); $\theta_1 = 30^\circ$, $\theta_2 = 44^\circ$, $\phi = 0.69$ and $R' =$

0.52 (SE cluster, Fig. 8c) This implies that under low fluid pressure condition ($P_f < \sigma_2$) only limited range of fracture orientations are susceptible to reactivate. In each case, for determining the absolute P_f magnitude, pole to vein data are plotted in 3D Mohr circles. Recent studies by Mondal and Acharyya (2018), documented the depth of faulting and fracturing in close vicinity of the study area (Chitradurga granite) to be ~2.4km. Similar depth of fracturing has also been reported by Acharyya and Mondal (2019), from the elliptical clasts of conglomerate bed within the Chitradurga schist belt. We have considered this depth for determining the magnitude of the maximum compressive stress (σ_1) during fracture formation, using $\sigma_1 = h\rho g$, where h = depth of fracturing in metabasalts (~2.4km), ρ = approximate bulk density of crust (2700 kg/m3), g = 9.8 m/sec2. Therefore, $\sigma_1 \geq 63.5$ MPa, when depth of fracturing in metabasalt~2.4km. The magnitude of the minimum compressive stress (σ_3) can be estimated using the stress intensity factor (fracture toughness), K_{IC}. K_{IC} for mode-I fractures, can be determined using the following equation (Lawn and Wilshaw, 1975; Atikinson, 1989).

$$K_{IC} = \sigma_3 Y (\pi a)^{1/2},$$

where σ_3 is the minimum far field stress acting normal to the crack, Y is a numerical modification factor to account for the crack geometry and edge effect, and 'a' is the crack half-length. Microstructural investigation suggests that the metabasalts are generally fine to medium grained, massive and consists of plagioclase laths and altered pyroxene with minor chlorite, ankerite and quartz (Gupta et al., 2014). Within the metabasalts, variably oriented larger phenocryst grains range from 2 mm to 8 mm in length. It is evident that the large phenocrysts were more susceptible to generate the initial fractures as compared to the medium to fine grained groundmass in these types of rocks. Therefore, we have considered that the length of the initial crack ranges from 2 mm to 8 mm (Brace, 1964). K_{IC} value for the metabasalts are

found to be 1.069 (Donovan, 2003). Considering this K_{IC} value and the range for fracture half-length (a), the $\sigma_3 Y$ value for the metabasalt ranges between 9-19 MPa. From this strength range we considered that 12 MPa is a reasonable estimate for the in situ tensile strength (similar to the laboratory strength) of the corresponding lithology. It may also be noted that, previous studies by Mondal and Acharyya, 2018, conducted in Chitradurga Granite, in close vicinity of the study area also regarded the magnitude of σ_3 ~10 MPa, to be a good estimation. Combining these estimations with the results obtained from the present studies, we constrained the value for σ_3 ~12MPa.

In each case we consider the limiting values for both maximum and minimum compressive stresses. Magnitude for the intermediate compressive stress (σ_2) is determined using the respective stress ratios (ϕ) for both high and low P_f respectively. Following Jolly and Sanderson (1997), the 3D Mohr circles are constructed using the above magnitudes of principal stresses and the angles determining the range of fracture orientations. Thus, well-defined P_f lines for both high P_f (P_f=53.2 MPa; Fig. 7b) and low P_f conditions (P_f=39.3 MPa; Fig. 7d, P_f=46.5, Fig. 8b and P_f=38.8, Fig. 8d) are obtained using the Fractend code (Github, 2017).

4.4 Dilation tendency, slip tendency and fracture susceptibility

Dilation tendency (T_d) and slip tendency (T_s) determine the propensity of any fracture orientation to reactivate through dilation or shearing, under a certain state of stress condition (Mazzarini et al., 2019). While, high dilation tendency ensures reactivation through dilation, high slip tendency elevates chances of opening through shearing (Ferrill et al., 1999). According to, Stephens et al., 2017, fracture planes suffer dilation when the difference between σ_1 and the normal stress acting on

the plane is close enough to the magnitude of differential stress($\sigma_D = \sigma_1 - \sigma_3$) and $T_d = (\sigma_1 - \sigma_n)/ \sigma_D$. Slip

tendency is denoted by the ratio of shear stress (σ_s) to normal stress (σ_n); ($T_s = \sigma_s/\sigma_n$) and also depends on

the frictional characteristics of the rock (Morris et al., 1996), along with the fracture plane orientation.

Under a particular state of stress condition if the ratio of shear stress to normal stress is significantly large,

then that particular fracture orientation is susceptible to reactivate. Fracture susceptibility (S_f), is defined

as the variation of fluid pressure (ΔP_f) within a fracture plane that can lead to fluid induced shear

reactivation (Mildren et al., 2002; Stephen et al., 2017). Such reactivations depend on the shear and

normal stresses acting on the fracture plane, along with the cohesion (= 0 in this case) and the static

coefficient of friction (μ_s); $S_f = \sigma_n - (\sigma_s/\mu_s)$.

Lower hemisphere equal area projections (see Fig. 9) of the poles to fracture (vein-filled) data help us to

understand the variation in dilation tendency, slip tendency and susceptibility of fractures with respect to

their orientations, under both high and low P_f conditions. The diagrams are prepared using Fractend code

(Github, 2017). It is evident from figure 9a, that the dilation tendency is high for the fracture orientations

which are at a high angle to the σ_3 axis, i.e., pole to these fractures form a well-defined cluster around σ_3.

These fractures show greater tendency towards dilational opening for both high and low P_f (Fig. 9a and

b). For fracture orientations having higher slip tendency, i.e., susceptible to shear opening, pole to the

fractures are at a low angle to the σ_3 axis. The fracture planes are therefore oriented at an angle to the

maximum compressive stress axis σ_1, condition favorable for shear reactivation for both, high and low P_f

(Fig. 9c and d). Fracture susceptibility, which involves variation in fluid pressure (ΔP_f) is low for the

fracture orientations having high dilation and slip tendencies, which indicates fluid-induced fracture

reactivation in metabasalts (Fig. 9e and f) in the study area.

350

4.5 Paleostress analysis

The shallow to moderaly plunging normal faults of the study area with prominent slip directions are used

to determine the stress regime under which these fractures and faults were formed and reactivated. Fault-

slip data (orientations of fault planes and slip directions) recorded from the field were used for paleostress

355   determination. Several methods are proposed for paleostress analyses using fault-slip data (e.g. Angelier,

1994; Dupin et al., 1993; Etchecopar et al., 1981; Gapais et al., 2000; Marrett and Allmendinger, 1990;

Ramsay and Lisle, 2000; Twiss and Unruh, 1998; Yamaji, 2000; Žalohar and Vrabec, 2007 and the

references therein). Since, the fault-slip analysis methods are well established, here we prefer to represent

only the salient aspects. The fault-slip analysis can be divided into two categories based on whether the

360   fault-slip data are viewed as representing kinematic or dynamic information (Blenkinsop 2006; Gapais et

al. 2000; Twiss & Unruh,1998) based on the following assumptions: (1) bulk state of stress is uniform

and movement on the fault planes are independent of each other; (2) slip on the fault plane occurs along

the direction of the maximum resolved shear stress under a given stress state (Wallace–Bott Hypothesis);

(3) faults are homogeneous and a part of the same tectonic event (Angelier, 1994; Gapais et al., 2000;

365   Gephart & Forsyth, 1984; Twiss & Unruh, 1998). In this study, we have determined the paleostress

direction, using fault-slip data measured from 73 shallow to moderately dipping normal faults (spatially

distributed) in the metabasalt by Right Dihedron method. Since, some of the fault planes show variation

in their strike orientations, the small amount of inhomogeneity in the data set is reduced in this process.

Thus, the data sets are segregated methodically into homogeneous data subsets using the 'Win_Tensor' software program (version 5.8.6; Delvaux and Sperner, 2003; Delvaux, 2011). In the present analysis all the collected data are represented in a single set and separation is done by using the Right Dihedron method without any sort of manual intervention. Following Delvaux and Sperner, 2003, the data is filtered on the basis of stress ratio (R), orientation of the stress axes and symmetry of the measured sets. Out of 73 data, 30 data are accepted with a low value of counting deviation and nominal counting values of 0 and 100 for σ_1 and σ_3 respectively. Thus, the best fitted reduced stress tensor is obtained for the accepted data subset (30 out of 73 fault data; see Fig. 10) at a "C" quality ranking. It also provides the relative orientations of the principal stress axes, stress ratio (R= 0.72) and stress regime index (R´=1.25). The NNE-SSW directed extension direction obtained from this paleostress analysis (see Fig. 10) coincides well with the regional D3 extension direction. Data rejected in this process to obtain the best fit stress tensor when treated separately yields, NNE-SSW oriented extension direction with small variations in the R and R´ values. According to Delvaux and Sperner (2003), the obtained stress regime index indicates a pure-strike slip domain which is in a good agreement with sinistral shearing along CSZ.

5 Discussions

5.1 Fabric development vs. regional tectonics

It has been mentioned earlier that the metabasalts of the study area lack any distinct visible foliation. However, the AMS analysis suggests, a prominent NNW-SSE to NW-SE oriented magnetic fabric in metabasalts. This magnetic fabric also matches well with the field foliation of the meta-sedimentary sequences, surrounding the metabasalts and is also parallel to the regional trend of CSZ (see Fig. 2). This

implies that the fabric in metabasalts of the study area must have been controlled by the regional D1/D2 deformation under NE-SW directed shortening that generated the field foliation in the meta-sedimentary sequences. The magnetic lineations in the metabasalts plunges due NNW through sub-vertical to SSE (Fig. 5b). In the previous studies, these variations in the plunge of the magnetic lineations had been interpreted as a consequence of superposed deformation (e.g., Mamtani and Sengupta, 2010; Mondal and Mamtani, 2013). Therefore, in the light of regional structural information and above discussions, it is inferred that these variations in magnetic lineations of the metabasalts are the manifestation of dome-basin geometry that were produced due to the superposition of D3 over D1/D2 regional deformation. Recently, Mondal (2018) documented similar results from the magnetic fabric analysis in adjacent Chitraurga granite. The studies by Bhatt et al., (2017); Mondal and Acharyya (2018), suggest that the D1/D2 deformation lasted between 2614 and 2555 Ma while the D3 deformation is approximated around ~2537 Ma.

5.2 Control of regional far-field stress on developing the brittle structures in Chitradurga region.

The above discussions suggest that (a) NNW-SSE oriented magnetic foliation developed during D1/D2 deformation under NE-SW directed shortening, (b) variation in plunge of magnetic lineation is a manifestation of dome-basin geometry on account of D3 deformation. It is argued that during D3 deformation under NW-SE to E-W directed shortening the CSZ evolved as a sinistral shear zone (Mondal and Acharyya, 2018). It may be noted that the angle between the mean orientation of the schist belt and the compression direction for D3 deformation are found to be ~45° which also supports the sinistral movement along Chitradurga shear boundary.

It is mentioned in sections 2 and 3 that, the study area is replete with a number of brittle structures such as fractures and faults. At places, these fractures are filled-up with quartz veins. Therefore, it is now essential to evaluate whether and how these brittle structures and their kinematics can be fitted to the regional far-field stresses responsible for deformation in the Chitradurga region. The quartz vein orientation data from northern part of the Chitradurga schist belt reveals that the vein emplacement took place during regional D3 deformation (Mondal and Mamtani, 2014). Recently, Mondal and Acharyya (2018), and Acharyya and Mondal (2019) suggested that the brittle structures (fractures/faults) in the Chitradurga granite (in close vicinity to the study area) are related to the D3 deformation. Moreover, paleostress investigation using fault-slip data also reveals NNE-SSW directed extension was dominant during D3 deformation. Apart from this, evidences of any later deformation, i.e., post D3 deformation, have not been recorded from the study area (from previous studies and as per our field observations). Thus, based on the present studies and above discussions, it is logically inferred that the formation of brittle structures (fractures/faults) as well as vein emplacement must be explained as a consequence of regional D3 deformation at a shallow depth. Mondal and Mamtani (2014) suggested that the Mulgund granite (2555 ± 6 Ma; Sarma et al., 2011), which lies in close vicinity to the metabasalts of the Chitradurga region, was emplaced syn-tectonically with CSZ. It is shown that the Mulgund granite underwent ductile deformation as it cooled and crystallized syn-tectonically with D3 deformation. The ductile deformation features in the granite were then superimposed by brittle structures during late D3, when the granite was fully solidified and had achieved a shallow depth (Mondal and Mamtani, 2016).Since both the lithologies (metabasalts and granite) have undergone same deformation and the fractures in them developed syntectonically with adjacent CSZ, it is favourable to interpret that the brittle structures, such as fractures

and faults in metabasalts developed on account of late D3 deformation under NW-SE to E-W directed compression at a shallow depth of about ~ 2.4 Km. For evaluating the nature (mode) of fracturing in the metabasalts of the study area, we used tensile strength (T) to be12 MPa (from BTS studies). We estimated $\Delta\sigma$= 51.5 MPa, which is greater than 4T, suggesting that the fractures in the metabasalts are not purely tensile, except for the cracks parallel to D3 shortening direction. However, the calculated value of $\Delta\sigma$ is less than 5.7T, indicating that the normal stress on the fractures are not purely compressive also. Therefore, the value of $\Delta\sigma$ satisfies $4T < \sigma_1 - \sigma_3 < 5.7\,T$ (Sibson, 2000), indicating that these fractures in the study area are extensional shear mode fractures.

440

5.3 Regional tectonics and the mechanism of fracturing, faulting

We discussed earlier in sect. -3, that the fractures and faults recorded in the metabasalts show a wide range of orientations with NNW-SSE maxima and WNW-ESE to NE-SW sub-maxima respectively (Fig. 4b). Among which, fractures trending along WNW-ESE to E-W are sub-parallel to the D3 (late phase) shortening direction. As previously mentioned in sect. -3, these WNW-ESE trending fractures have been regarded as tensional fractures. Similar orientations have also been recorded and interpreted as tensile fractures from the micro-granitoid enclaves in Chitradurga granite as evident from the studies of Mondal and Acharyya (2018). However, it is essential to explain the predominance of fractures and faults along the NNW-SSE orientation (forming the maxima). In order to explain this, we refer to the pre-existing fabric in the metabasalts of the study area, i.e., the NNW-SSE to NW-SE oriented magnetic fabric developed during D1/D2 regional deformation (Fig. 5a). Earlier studies suggest, that fractures are more likely to propagate along a pre-existing anisotropy, if and when the anisotropy is favorably oriented with

respect to the regional stress field (Ikari et al., 2015). The CSZ being a sinistral shear zone exhibits a pure strike slip stress regime, coeval with D3 deformation (NW-SE to E-W directed shortening).

455 In the later phase of D3 deformation, the favorably oriented NNW-SSE fabrics were reactivated under a compatible stress field, thereby, causing reactivation of the pre-existing fabrics in the metabasalts. This however, fails to justify the occurrence of the ~NW-SE and ~NE-SW oriented fractures within the metabasalts. From field investigations, the NE-SW oriented fractures show dextral movements, while the NNW-SSE and NW-SE oriented fractures are recorded with sinistral movements respectively (see Fig.

460 3c and d). However, the fracture disposition and consistency in their respective orientations indicate that all of these fractures are coeval, related to the same deformational event and have been reactivated under similar stress conditions. Moreover, any other brittle deformational event post D3, have not been recorded from the study area as mentioned earlier. Therefore, we need to explain the occurrence of such variably oriented fractures/faults within a single kinematic framework. The NNW-SSE and NW-SE orientations

465 are most likely to be sinistral, whereas NE-SW orientations form the dextral shear components respectively, considering CSZ to be the sinistral shear boundary. (See Fig. 11b and 4b, c). Thus, the NNW-SSE to NW-SE (P, Y and R) and the NE-SW to ENE-WSW (X and R′) fractures coincide with the shear components of a riedel shear system considering the angle of internal friction (Φ) in metabaslts of the study area to be ~30˚. It may be noted that the value of Φ is approximated from the Uniaxial

470 Compressive Strength (UCS) studies of the metabasalts core samples following Sivakugan et al., 2014.

These fracture planes (P, Y, R, X and R′) acted as pathways for fluid flow and vein emplacement during the late D3 deformation.

5.4 Understanding the mechanism of fluid flow and vein emplacement in Chitradurga region

475 In order to explain the vein emplacement mechanism along these weak zones we need to consider the fluid pressure conditions that prevailed at the time of vein emplacement. In sect. 4.4, we mentioned earlier that the lower hemisphere equal area projection of pole to vein data shows girdle distribution, indicating high P_f condition (~53.2 MPa; $>\sigma_2$) in the study area. Under such high P_f conditions, veins were emplaced along all possible orientations, including NNW-SSE, NW-SE, WNW-ESE, NE-SW and ENE-WSW

480 trending fractures. The building fluid pressure surpassed the normal stresses acting on the fracture wall, and hence, fluid burped into the weak planes leading to fluid-induced reactivation of the fractures, promoting vein emplacement along them (Fig. 11c). However, the NNW-SSE trending veins show greater thickness and abundance with respect to other orientations (see Fig. 4d and 3e). We found that pole to these veins (NNW-SSE trending orientations) lie within the warm zones of the stereoplots obtained from

485 the Fractend code (Github, 2017), indicating higher dilation tendencies (see Fig. 9a and 9b). In Fig. 9a and 9b, it is perceived that pole to these orientations form a cluster around the σ_3 stress axis. Similarly, pole to the orientations trending NW-SE and NE-SW respectively, have higher slip tendencies, indicating shear reactivation along them (Fig. 9c and d). Most of the poles to the NNW-SSE trending orientations lie within the overlapping warm zones, indicating high potential to reactivate in both shear and dilation

490 mode (high slip and dilation tendencies). These orientations are susceptible for dilation as well as shear reactivation, depending on the predominance of fluid pressure and availability of fluid for inducing

dilation or shear reactivation. Availability of fluid significantly reduces the effective normal stress (σ_n' $=\sigma_n- P_f$); where σ_n' and σ_n are the effective normal stress and normal stress respectively) acting on the fracture planes (see Fig. 11c and d). Under this condition, fluid burps into the fractures leading to a significant drop in the fluid pressure. This sudden drop in the fluid pressure reduces the solubility of fluid materials promoting deposition of vein followed by sealing of the pathways (Cox et al., 1991, 2001). Pathways thus remains sealed till the next cycle of fluid pressure build up, fracture reactivation and vein deposition. However, in between two such cycles of high fluid pressure, intermediate low fluid pressure cycles persist, during which fluid pressure might not be substantially high to reactivate all the pre-existing pathways. Thus, a high fluid pressure cycle is followed by subsequent pulses of low fluid pressure causing selective reactivation of some of the pre-existing orientations. The orientations represented by the individual clusters (WSW, NE and SE) can be reactivated selectively depending on their respective orientation to the tectonic stress field and the fluid pressure magnitude. Hence, it is envisaged that, these cycles of high and low P_f conditions might have been repeated multiple times (n-times) until the fluid source was completely exhausted. In the present case, the low P_f conditions are interpreted by discretely analyzing the clusters within the girdle distribution of pole to vein data in the lower hemisphere equal area projection. (see sect. 4.4). Such low P_f could not surpass the normal stresses of all the pre-existing pathways. And only the NNW-SSE oriented ones (related to the magnetic fabric of the metabasalts) having high dilation and slip tendencies were favorably oriented for reactivation and fluid flow. The above mechanism of *fault-valve action* is supported with field evidences showing occurrences of thick quartz veins enclosing angular chunks of metabasalt hosts with multiple sub-parallel fault planes (identified from the slickenside lineations), see Fig. 3e & 3f. Quartz veins with multiple median lines indicate

predominance of crack-seal mechanism due to cyclic fluid ingression (Fig. 3g). This suggests that the process of fracturing, fracture reactivation through faulting and vein emplacement (*fault-valve* action) prevailed throughout the D3 deformation. Thus, the process of new fracture formation and reactivation were continuously persistent during the entire late D3 phase, with intermittent episodes of vein emplacement under both high and low P_f conditions.

7 Conclusions

In the present study, we commented on the vein emplacement mechanism of the Chitradurga greenstone belt (Dharwar craton, south India). We analysed the magnetic fabric data recorded from AMS analysis of the metabasalt that hosts the quartz veins. 3D Mohr circle and paleostress analysis have been used to evaluate the vein emplacement vs. regional deformation. Following are the main findings and conclusions from the study:

1. The NW-SE oriented magnetic fabric recorded in the metabasalts (as evident from the AMS analysis) is a product of the D1/D2 regional deformation on account of NE-SW directed shortening. This fabric was also favourably oriented and therefore, suitable for fracture propagation in relation to the prevailing stress field.

2. D3 deformation manifested by NW-SE to E-W directed shortening was coeval with the sinistral movement along CSZ. It is concluded that during late D3 deformation all pre-existing fabrics and the ones constituting the riedel shear system were reactivated, with CSZ acting as a shear boundary.

3. The variably oriented fractures and faults i.e., the NNW-SSE, NW-SE, WNW-ESE, NE-SW and ENE-WSW oriented ones are identified as the P, Y, R, T, X and R´ shear components of the riedel shear system. The NNW-SSE oriented shears (P, Y and R) are abundant owing to their favourable correspondence with the pre-existing AMS fabric.

4. Paleostress analysis using fault-slip data recorded from field studies reveals NNE-SSW directed extension, asserting reactivation under a WNW-ESE directed compression (related to D3 deformation).

5. Vein emplacement took place under both high and low P_f conditions. It is envisaged that multiple number of such alternating high and low P_f cycles prevailed in the process of fluid flow and vein emplacement in the region.

6. Vein emplacement took place along all possible orientations. Evidences of *fault-valve behaviour* and fluid induced fracture/fault reactivation have been recorded from field studies. However, the NNW-SSE trending orientations having higher values of slip and dilation tendencies, channelized fluid during both high and low P_f conditions, thereby attaining maximum vein thickness.

7. The process of fracture formation, reactivation and faulting prevailed under a far field compression related to late D3 deformation. However, intermittent episodes of fluid pressure build up led to fluid induced faulting, rupturing and vein emplacement in the region.

550

Author contribution: SB: conceptualization, methodology, data curation, formal analysis, writing. TKM: supervision, conceptualization, methodology, data curation, funding acquisition, writing.

Competing interests: The authors declare that they have no conflict of interest.

555

Acknowledgments

The study is funded by DST-SERB (File No. ECR/2015/000079) and RUSA 2.0 to TKM. This study is a part of SB's doctoral research; being funded by DST Inspire (IF170912). Geological Survey of India (Bangalore) is acknowledged for helping with logistic support and discussions during fieldwork. Prof.
560 Manish A. Mamtani is thanked for allowing the authors to use KLY-4S Kappabridge system (IIT Kharagpur, India) for AMS analysis. Prof. Arindam Basu and Dr. Bikash K. Ram are thanked for helping with tensile strength measurements using GCTS$^©$ at IIT Kharagpur, India. Detailed reviews by Prof. Francesco Mazzarini and Prof. C. Pascal helped to improve the paper considerably. Editorial handling by Prof. Roger Soliva is gratefully acknowledged. Assistance provided by Ayan Patsa, Subha Saha and
565 Swarnasree Mondal are acknowledged. SB also acknowledges the wholehearted support of Sunil Kumar Bhowmick and Gouri Bhowmick.

References

Acharyya, S.S., Mondal, T.K.: Stress enhanced tensile fractures in elliptical clast in conglomerate. Journal
of Structural Geology 122 (2019) 81–88, https://doi.org/10.1016/j.jsg.2019.02.001, 2019.

Angelier, J., 1994.: Fault slip analysis and palaeostress construction. In: Hancock, P.L. (Ed.), Continental
Deformation. Pergamon Press, London.

ASTM (2001) American Society for Testing and Materials. ASTM Standards on Disc, 04.08. West
Conshohocken, PA, 2001.

Attewell, P.B., Sandford, M.R.: Intrinsic shear strength of a brittle, anisotropic
Rock-I. Experimental and mechanical interpretation. Int. J. Rock Mech. Min.
Sci. Geomech. Abstract. 11, 423-430, 1974.

Atkinson, B.K., and Meredith, P. G., 1989. Experimental fracture mechanics data for rocks and minerals,
in Atikinson, B. K., ed., Fracture mechanics of rocks: London, Academic Press. 477-525.

Aydin A, Basu A.: The use of Brazilian test as a quantitative measure of rock weathering. Rock Mech
Rock Eng 39:77–85, https://doi.org/10.1007/s00603-005-0069-0, 2006.

Baer, G., Beyth, M., Reches, Z.: Dikes emplaced into fractured basement, Timna Igneous Complex,
Israel. Journal of Geophysical Research 99, 24039–24051, https://doi.org/10.1029/94JB02161,
1994.

Basu, A., Mishra, D.A., Roychowdhury, K.: Rock failure modes under uniaxial compression, Brazilian,
and point load tests. Bull EngGeol Environ (2013) 72:457–475,
http://dx.doi.org/10.1007%2Fs10064-013-0505-4, 2013.

Beckinsale, R. D., Drury, S. A., Holt, R. W.: 3305–Myr old gneisses from south
Indian craton. Nature 283, 469–470, 1980.

Bhatt, S., Rana, V., Mamtani, M.A.: Deciphering relative timing of fabric development in granitoids
withsimilar absolute ages based on AMS study (Dharwar Craton, South India). Journal of
Structural Geology 94 (2017) 32-46,

https://ui.adsabs.harvard.edu/link_gateway/2017JSG....94...32B/doi:10.1016/j.jsg.2016.11.002,
2017.

595 Blenkinsop, G. T.: Kinematic and dynamic fault slip analyses: implications from the surface rupture of
the 1999 Chi–Chi, Taiwan, earthquake, Journal of Structural geology, 28, 1040–1050,
https://doi.org/10.1016/j.jsg.2006.03.011, 2006.

Boullier, A. M., Robert, F.: Palaeoseismic events recorded in Archaean gold quartz vein networks, Val
d'Or, Abitibi, Quebec, Canada. Journal of Structural Geology14, 161–179,
600 https://doi.org/10.1016/0191-8141(92)90054-Z, 1992.

Chadwick, B., Vasudev, V. N., Hedge, G. V.: The Chitradurga schist belt and its adjacent plutonic rocks
NW of Tungabhadra, Karnataka: a duplex in the late Archean convergent setting of the Dharwar
craton. Journal of the Geological Society of India 61, 611–613, 2003.

Chadwick, B., Ramakrishnan, M., Vasudev, V. N., Viswanatha, M. N.: Facies Distributions and Structure
605 of a Dharwar Volcano sedimentary Basin: Evidence for Late Archaean transpression in Southern
India? Journal of the Geological Society of London 146, 825–834, 1989.

Chakrabarti, C., Mallick, B. S., Pyne, T. K., Guha, D.: A manual of the Geology of India. Geological
Survey of India, Kolkata, 2006.

Chardon, D., Peucat, J.–J., Jayananda, M., Choukroune, P., Fanning, C.M.: Archaean granite–greenstone
610 tectonics at Kolar (south India): interplay of diapirism and bulk inhomogeneous contraction during
juvenile magmatic accretion. Tectonics 21, 1–17, https://doi.org/10.1029/2001TC901032, 2002.

Cox, S. F., Knackstedt, M. A., Braun, J.: Principles of structural control on permeability and fluid flow
in hydrothermal systems. Society of Economic Geologists Reviews 14, 1–24, 2001.

Cox, S. F.: Faulting processes at high fluid pressures: an example of fault–valve behaviour from the
615 Wattle Gully Fault, Victoria, Australia. Journal of Geophysical Research 100, 12841–12860,
https://doi.org/10.1029/95JB00915, 1995.

Cox, S. F., Wall, V. J., Etheridge, M. A., Potter, T. F.: Deformational and metamorphic processes in the
formation of mesothermal vein–hosted gold deposits — examples from the Lachlan Fold Belt in

central Victoria, Australia. Ore Geology Reviews 6, 391–423, https://doi.org/10.1016/0169-1368(91)90038-9, 1991.

Cucci, L., Luccio, F.D., Esposito, A., Ventura, G.: Vein networks in hydrothermal systems provide constraints for the monitoring of active volcanoes. Scientific reports 7:146, https://dx.doi.org/10.1038%2Fs41598-017-00230-8, 2017.

Delaney, P. T., Pollard, D. D., Zioney, J. I., McKee, E. H.: Field relations between dikes and joints: emplacement processes and palaeostress analysis. Journal of Geophysical Research 91 (B5), 4920–4938, doi.org/10.1029/JB091iB05p04920, 1986.

Delvaux, D.: EGU General Assembly. Win-tensor, an Interactive Computer Program for Fracture Analysis and Crustal Stress Reconstruction, vol. 13 , Geophysical Research Abstract, Vienna, 2011

Delvaux, D., Sperner, B.: Stress tensor inversion from fault kinematic indicators and focal mechanism data: the TENSOR program. In: Nieuwland, D. (Ed.), New Insights into Structural Interpretation and Modelling: Geol. Soc. Lond. Special Publication 212, 75–100, 2003.

Donath, F.A.: Experimental study of shear failure in anisotropic rocks. Geol. Soc. Am. Bull. 72, 985-990, 1961.

Donovan, J. G. 2003. Fracture toughness based model for the prediction of power consumption, product size, and capacity of jaw crushers. Doctoral dissertation, Virginia Polytechnic Institute and State University.

Dupin, J. M., Sassi, W., Angelier, J.: Homogeneous stress hypothesis and actual fault slip: a distinct element analysis, Journal of Structural Geology 15, 1033–1043, doi.org/10.1016/0191-8141(93)90175-A, 1993.

Etchecopar, A., Vasseus, G., Daigniers, M. : An inverse problem in microtectonics for the determination of stress tensor from fault striation analysis, Journal of Structural Geology 3, 51–65, DOI: 10.1016/0191-8141(81)90056-0, 1981.

Ferrill, D.A., Winterle, J., Wittmeyer, G., Sims, D., Colton, S., Armstrong, A., Morris, A.P., 1999. Stressed rock strains groundwater at Yucca Mountain, Nevada. GSA Today 9, 1–8.

Gapais, D., Cobbold, P. R., Bourgeois, O., Rouby, D., de Urreiztieta, M.: Tectonic Significance of fault–slip data, Journal of structural Geology. 22, 881–888, doi.org/10.1016/S0191-8141(00)00015-8, 2000.

Gephart, J. W., Forsyth, D. W.: An improved method for determining the regional stress tensor using earthquake focal mechanism data: application to the San Fernando earthquake sequence, Journal Geophysical Research 89(B11), 9305–9320, **doi.org/10.1029/JB089iB11p09305**, 1984.

GitHub, 2017. FracTend MATLAB code. https://github.com/DaveHealy-Aberdeen/FracTend

Gopalakrishna, G., Shareef, M., Nagesh, P.C., 2018. Shear-Controlled Gold Mineralization of G. R.Halli Area of Chitradurga Schist Belt, DharwarCraton: Insights from Fluid Inclusion Study. Open Journal of Geology, 8, 662-673, DOI: 10.4236/ojg.2018.87039 , 2018.

Gudmundsson, A., 2011. Rock Fractures in Geological Processes. Cambridge UniversityPress.

Gupta, S., Jayananda, M., Fareeduddin, 2014. Tourmaline from the Archean G.R. Halli Gold Deposit, Chitradurga Greenstone Belt, Dharwar Craton (India): Implications for the Gold Metallogeny. Geoscience Frontiers, 5, 877-892, doi.org/10.1016/j.gsf.2013.12.004, 2014.

Hoek, E.: Fracture of anisotropic rock. J. South Afr. Inst. Min. Metal. 64 (10), 501-518, 1964.

Hrouda, F., Chlupáčová, M., Pokorný, J.: Low–field variation of magnetic susceptibility measured by the KLY–4S Kappabridge and KLF–4A magnetic susceptibility meter: Accuracy and interpretational programme. Studia Geophysica et Geodaetica 50, 283–299, 2006.

Ikari, M.J., Neimeijer, A.R., Marone, C.: Experimental investigation of incipient shear failure in foliated rock. Journal of Structural Geology 77, 82-91, doi.org/10.1016/j.jsg.2015.05.012, 2015.

ISRM, Suggested methods for determining tensile strength of rock materials. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., Vol. 15, 99-103, 1978.

Jayananda, M., Chardon, D., Peucat, J.–J., Capdevila, R.: 2.61 Ga potassic granites and crustal reworking in the western Dharwar craton, southern India: tectonic, geochronologic and geochemical constraints. Precambrian Research 150, 1–26, DOI: 10.1016/j.precamres.2006.05.004, 2006.

Jelínek, V.: Characterization of magnetic fabric of rocks. Tectonophysics 79, T63–T67, DOI:10.1016/0040-1951(81)90110-4, 1981.

Jolly, R.J.H., Sanderson, D.J. : A Mohr circle reconstruction for the opening of a pre-existing fracture. Journal of Structural Geology 19, 887-892, DOI. 10.1016/S0191-8141(97)00014-X, 1997

Lahiri, S., Mamtani, M.A.: Scaling the 3-D Mohr circle and quantification of paleostress during fluid pressure fluctuation–Application to understand gold mineralization in quartz veins of Gadag (southern India). Journal of Structural geology 88, 63–72, doi.org/10.1016/j.jsg.2016.05.003, 2016.

Lawn, B.R., and Wilshaw, T.R., 1975. Fracture of brittle solids: Cambridge, England, Cambridge University Press.

Logan, J. M., Dengo, C. A., Higgs, N. G., Wang, Z. Z.: Fabrics of experimental fault zones: their development and relationship to mechanical behaviour. In: Evans, B. & Wong, T. (eds) Fault Mechanics and Transport Properties of Rocks. Academic Press, San Diego, CA, 33–67, 1992.

Loock, S., Diot, H., Van Wyk de Vries, B., Launeau, P., Merle, O., Vadeboin, F., Petronis, M.S.: Lava flow internal structure found from AMS and textural data: An example in methodology from the Chaîne des Puys, France. Journal of Volcanology and Geothermal Research 177, 1092–1104, doi.org/10.1016/j.jvolgeores.2008.08.017, 2008.

Maffione, M., Hernandez-Moreno, C., Ghiglione, M.C., Speranza, F., van Hinsbergen, D.J.J., Lodolo, E.: Deformation of the Southern Andes since the Late Cretaceous: constraints from anisotropy of magnetic susceptibility (AMS). Tectonophysics 665, 236–250, doi.org/10.1016/j.tecto.2015.10.008, 2015.

Mamtani, M.A., Greiling, R.O.: Granite emplacement and its relation with regional deformation in the Aravalli Mountain Belt–inferences from magnetic fabric. Journal of Structural Geology 27, 2008–2029, doi.org/10.1016/j.jsg.2005.06.004, 2005.

695 Mamtani, M.A., Sengupta, P.: Significance of AMS analysis in evaluating superposed folds in quartzites. Geological Magazine 147, 910–918, DOI: 10.1017/S0016756810000397, 2010

Marchesini, B., Garofalo, P.S, Menegon, L., Mattila, J., Viola, G.: Fluid-mediated, brittle–ductile deformation at seismogenic depth –Part 1: Fluid record and deformation history of fault veins in a nuclear waste repository (Olkiluoto Island, Finland). Solid Earth, 10, 809–838, 700 doi.org/10.5194/se-10-809-2019, 2019.

Marrett, R., Allmendinger, R. W.: Kinematic analysis of fault–slip data , J.Struc.Geol. 12, 973–986. doi.org/10.1016/0191-8141(90)90093-E, 1990.

Martínez-Poza, A. I., Druguet, E., Castaño, L. M., Carreras, J.: Dyke intrusion into a pre-existing joint network: The Aiguablava lamprophyre dyke swarm (Catalan Coastal Ranges). Tectonophysics 705 630, 75–90, doi.org/10.1016/j.tecto.2014.05.015, 2014.

Mazzarini, F., Isola, I.: Hydraulic connection and fluid overpressure in upper crustal rocks: evidence from geometry and spatial distribution of veins at Botrona quarry, southern Tuscany, Italy. Journal of Structural Geology 29, 1386-1399, doi.org/10.1016/j.jsg.2007.02.016, 2007.

Mazzarini, F., Musumeci, G., Viola, G., Garofalo, P.S., Mattila, J.: Structural and lithological control on 710 fluid circulation, dilation and ore mineralization (Rio Albano mine, Island of Elba, Italy). Journal of Structural Geology 126 (2019) 210–230, doi.org/10.1016/j.jsg.2019.06.012, 2019.

McKeagney, C.J., Boulter, C.A., Jolly, R.J.H., Foster, R.P.: 3-D Mohr Circle analysis of vein opening, Indarama lode-gold deposit, Zimbabwe: implications for exploration. Journal of Structural Geology 26, 1275-1291, doi.org/10.1016/j.jsg.2003.11.001, 2004.

715 Mondal, T.K., Acharyya, S.S.: Fractured micro-granitoid enclaves: a stress marker. Journal of Structural Geology 113, 33–41, DOI: 10.1016/j.jsg.2018.05.011, 2018.

Mondal, T.K.: Evolution of fabric in Chitradurga granite (south India)-A study based on microstructure, anisotropy of magnetic susceptibility (AMS) and vorticity analysis. Tectonophysics 723, 149–161, doi.org/10.1016/j.tecto.2017.12.013, 2018.

720 Mondal, T.K., Mamtani, M.A.: Palaeostress analysis of normal faults in granite implications for interpreting Riedel shearing related to regional deformation. Journal of Geological Society 173, 216–227, doi.org/10.1144/jgs2014-136, 2016.

Mondal, T.K., Mamtani, M.A.: Fabric analysis in rocks of the Gadag region (southern India)-implications for time relationship between regional deformation and gold mineralization. Tectonophysics 629, 725 238–249, DOI: 10.1016/j.tecto.2013.09.021, 2014.

Mondal, T.K., Mamtani, M.A.: 3-D Mohr circle construction using vein orientation data from Gadag (southern India) e implications to recognize fluid pressure fluctuation. J. Struct. Geol. 56, 45-56, doi.org/10.1016/j.jsg.2013.08.005, 2013.

Mildren, S.D., Hillis, R.R., Kaldi, J.: Calibrating predictions of fault seal reactivation in the Timor Sea. 730 APPEA J.42 (1), 187–202, 2002

Morris, A., Ferrill, D.A., Henderson, D.B., 1996. Slip-tendency analysis and fault reactivation. Geology 24, 275–278.

Naqvi, S.M., Rogers, J.J.W.: Precambrian geology of India: Oxford monographs on geology and geophysics No. 6. Oxford University Press, New York. 1987

735 Petit, J. P., Wibberley, C. A. J., Ruiz, G.: `Crack±seal', slip: a new fault valve mechanism? Journal of Structural Geology 21, 1199-1207, 1999, 10.1016/S0191-8141(99)00038-3.

Ramakrishnan, M., Vaidyanadhan, R., 2010. Geology of India. Vol. 1. Geological Society of India, Bangalore.

Ramadass, G., Himabindu, D., Srinivasulu, N., 2003. Structural appraisal of the Gadag schist belt from 740 gravity investigations. Proceedings of the Indian Academy of Sciences (Earth and Planetary Science) 112, 577–586.

Ramsay, J.G. & Lisle, R.J.: The Techniques of Modern Structural Geology. Vol. 3: Applications of Continuum Mechanics in Structural Geology. Academic Press, London, 2000.

Raposo, M.I.B., D'Agrella–Filho, M.S., Pinese, J.P.P.: Magnetic fabrics and rock magnetism of Archaean 745 and Proterozoic dike swarms in the southern São Francisco Craton, Brazil. Tectonophysics 443, 53–71 doi.org/10.1016/j.tecto.2007.08.001, 2007.

Sanderson, D. J., Zhang, X., 1999. Critical stress localization of flow associated with deformation of well–fractured rock masses, with implications for mineral deposits. In: McCaffrey, K. J. W., Lonergan, L. and Wilkinson, J. J. (Eds.) Fractures, Fluid Flow and Mineralization. Geological Society of London, Special Publications 155, 69–81.

Sarma, D. S., Fletcher, I. R., Rasmussen, B., McNaughton, N. J., Mohan, M. R., Groves, D. I.: Archean gold mineralization synchronous with late cratonization of the Western Dharwar Craton, India: 2.52 Ga U–Pb ages of hydrothermal monazite and xenotime in gold deposits. Mineralium Deposita 46, 273–288, DOI: 10.1007/s00126-010-0326-3, 2011.

Sibson, R. H.: A brittle failure mode plot defining conditions for high flux–flow. Economic Geology 95, 41–48, 10.2113/gsecongeo.95.1.41, 2000.

Sibson, R. H., Robert, F., Poulsen, K. H.: High–angle reverse faults, fluid–pressure cycling, and mesothermal gold–quartz deposits. Geology 16, 551–555, doi.org/10.1130/0091-7613(1988)016<0551:HARFFP>2.3.CO;2, 1988

Sibson, R. H., Scott, J.: Stress/fault controls on the containment and release of over pressured fluids: examples from gold–quartz vein systems in Juneau, Alaska,Victoria, Australia, and Otago, New Zealand. Ore Geology Reviews 13, 293–306, 10.1016/S0169-1368(97)00023-1, 1998.

Sibson, R. H.: Structural permeability of fluid–driven fault–fracture meshes. Journal of Structural Geology 18, 1031–1043, doi.org/10.1016/0191-8141(96)00032-6, 1996.

Sibson, R. H.: Implications of fault–valve behaviour for rupture nucleation and recurrence. Tectonophysics 211, 283–293, doi.org/10.1016/0040-1951(92)90065-E, 1992.

Sivakugan, N., Das, B. M., Lovisa, J., Patra, C. R.: Determination of c and w of rocks from indirect tensile strength and uniaxial compression tests. International Journal of Geotechnical Engineering 8, 59-65, doi.org/10.1179/1938636213Z.00000000053, 2014.

Stephens, T.L., Walker, R.J., Healy, D., Bubeck, A., England, R.W., McCaffrey, K.J.: Igneous sills record far-field and near-field stress interactions during volcano construction: Isle of Mull, Scotland. Earth Planet. Sci. Lett. 478, 159–174. doi.org/10.1016/j.epsl.2017.09.003, 2017.

Tarling, D. H., Hrouda, F., 1993. The Magnetic Anisotropy of Rocks. Chapman and Hall, London.

Taylor, P.N., Chadwick, B., Moorbath, S., Ramakrishnan, M., Viswanatha, M.N.: Petrography, chemistry and isotopic ages of Peninsular Gneiss, Dharwar acid volcanic rocks and the Chitradurga granite with special reference to the late Archaean evolution of the Karnataka craton. Precambrian Research 23, 349- 375. 10.1016/0301-9268(84)90050-0, 1984.

Thyng, K.M., Greene, C.A., Hetland, R.D., Zimmerle, H.M., DiMarco, S.F,: True Colors of Oceanography Guidelines for Effective and Accurate Colormap Selection. Oceanography, 9-13, doi.org/10.5670/oceanog.2016.66, 2016

Tsidzi, K. E. N.: The influence of foliation on point load strength anisotropy of foliated rocks. Engineering Geology 29, 49–58. 10.1016/0013-7952(90)90081-B, 1990.

Twiss, R. J., Unruh, J. R.: Analysis of fault slip inversions; do they constrain stress or strain rate? , Journal of Geophysical Research 103 (B6), 12205–12222, doi.org/10.1029/98JB00612.1998.

Vishnu, C. S., Lahiri, S., Mamtani, M. A.: The relationship between magnetic anisotropy, rock-strength anisotropy and vein emplacement in gold-bearing metabasalts of Gadag (South India). Tectonophysics 722, 286-298, doi.org/10.1016/j.tecto.2017.09.011. 2018.

Yamaji, A.: Genetic algorithm for fitting a mixed Bingham distribution to 3D orientations: a tool for the statistical and paleostress analyses of fracture orientations. Island Arc 25, 72-83. DOI: 10.1111/iar.12135, 2016.

Yamaji, A., Sato, K.: Clustering of fracture orientations using a mixed Bingham distribution and its application to paleostress analysis from dike or vein orientations. Journal of Structural Geology 33, 1148-1157. DOI: 10.1016/j.jsg.2011.05.006, 2011.

Yamaji, A., Sato, K., Tonai, S.: Stochastic modeling for the stress inversion of vein orientations: Paleostress analysis of Pliocene epithermal veins in south western Kyushu, Japan. Journal of Structural Geology 32, 1137–1146. DOI: 10.1016/j.jsg.2010.07.001, 2010.

Yamaji, A.: The multiple inverse methods: a new technique to separate stresses from heterogeneous fault-slip data, Journal of Structural Geology 22, 441–452. DOI: 10.1016/S0191-8141(99)00163-7 2000.

800 Žalohar, J., Vrabec, M.: Paleostress analysis of heterogeneous fault–slip data: the Gauss method, Journal of Structural Geology 29, 1798–1810. DOI: 10.1016/j.jsg.2007.06.009, 2007.

805

810

Figures:

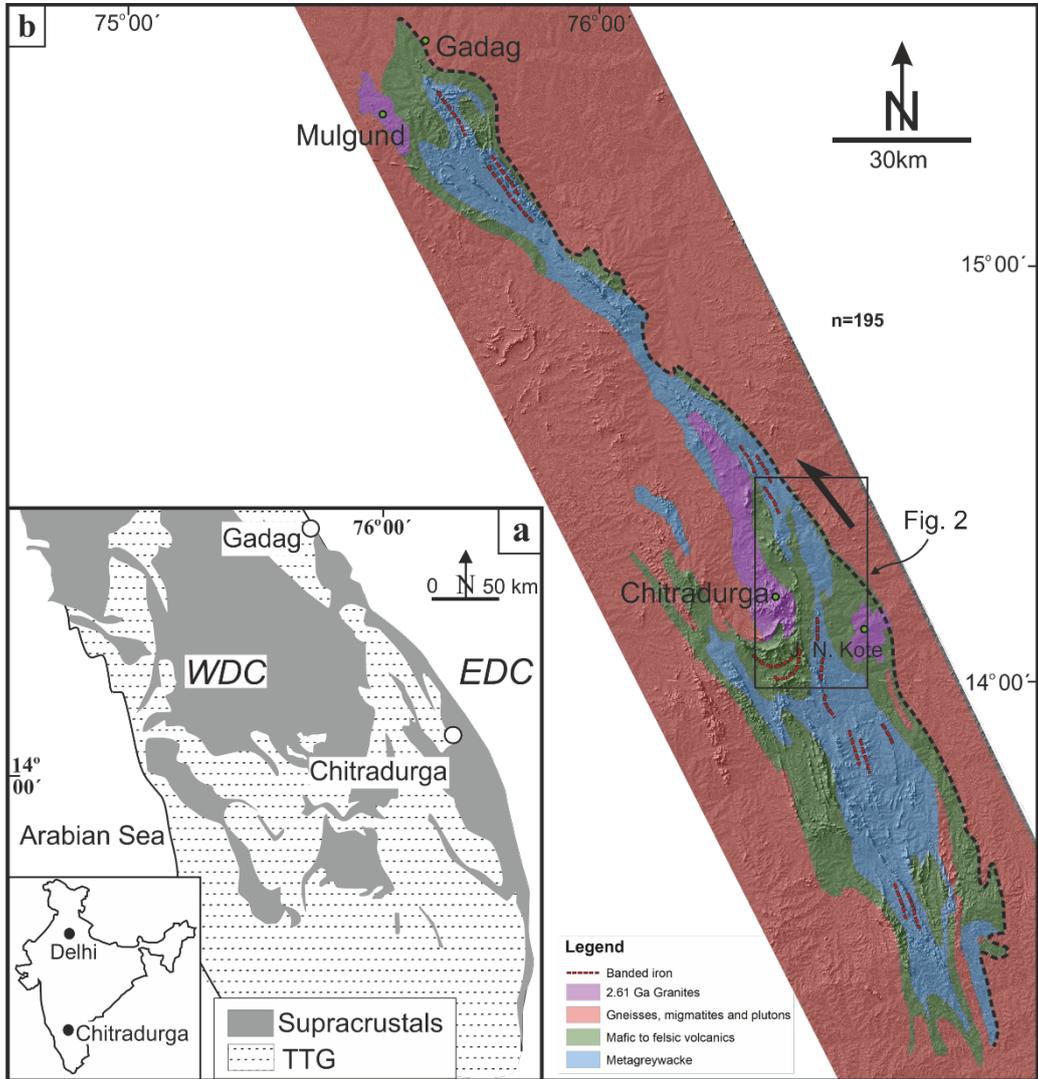



Figure 01: (a) Regional map of western Dharwar craton, South Indian Shield [after Chadwick et al., 2003]. Inset shows the map of India. EDC = Eastern Dharwar Craton; WDC = Western Dharwar Craton, TTG=Tonalite-Trondhjemite-Granodiorite; Supracrustals=volcano-sedimentary assemblages. (b) Regional geological map (DEM) of the Chitradurga Schist Belt [modified after Jayananda et al., 2013]. Dotted line (in *b*) marks the eastern boundary of the Chitradurga Schist Belt, representing the Chitradurga Shear Zone (CSZ). Rectangular box near Chitradurga demarcates the study area.

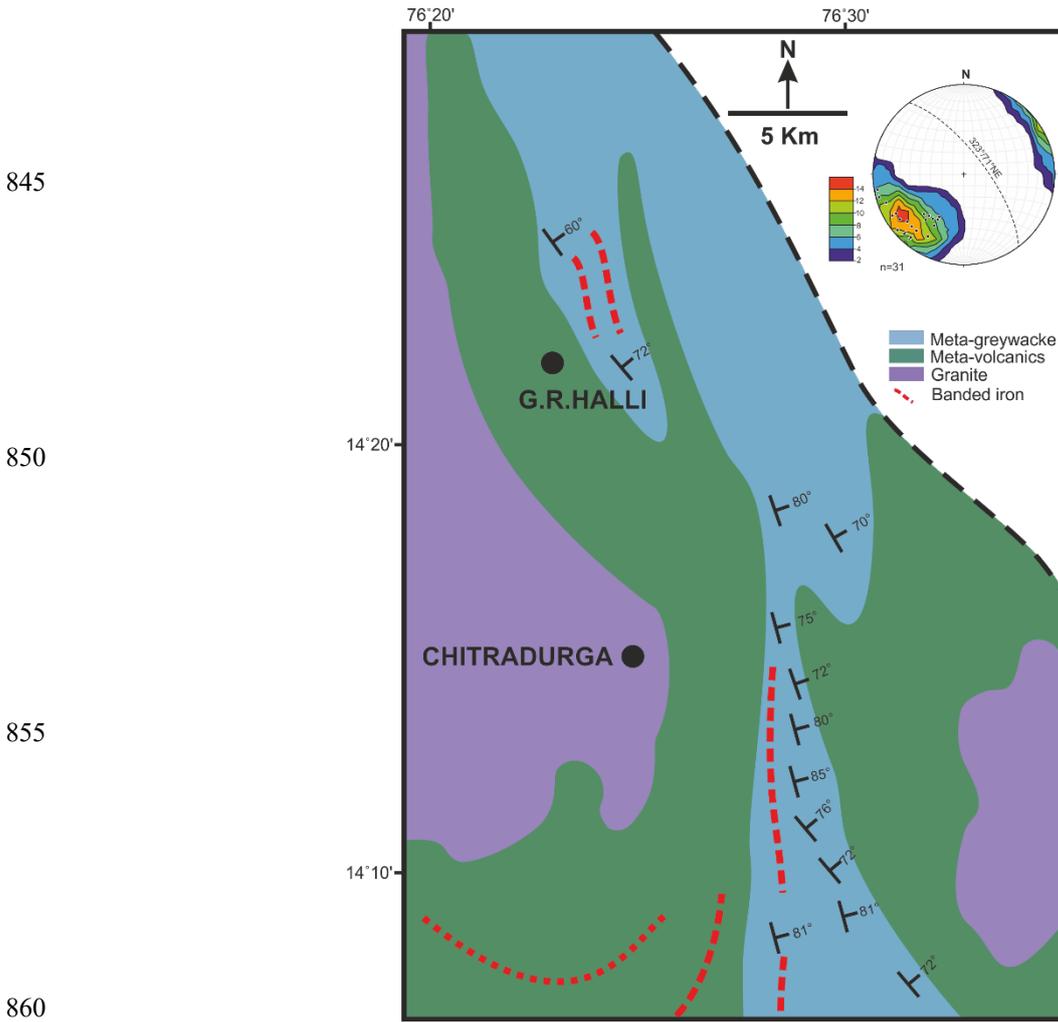



Figure 02: Geological map of the study area showing the foliation trends of the supracrustals. Lower hemisphere equal area projection shows the pole to foliation planes recorded from the region. Note that the mean foliation (dotted great circle) is 323º/71ºNE which is parallel to the CSZ (n= number data). Color scheme of the legend indicates variation in the contour density.

875

880

885

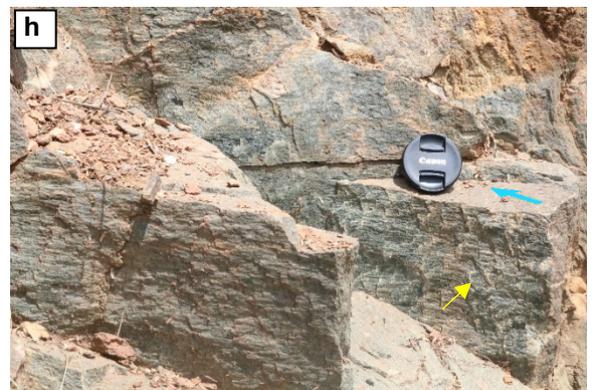
890

895

Figure 03. Field photographs from the study area. (a) Criss-cross orientation of quartz veins in metabasalt. (b) Close-up of a quartz vein in metabasalt showing crystal growth direction perpendicular to the vein wall. (c) Cross-cutting nature in quartz veins showing dextral displacement (marked by yellow half-arrows). (d) Wing cracks filled up with quartz veins associated with sinistral shearing (marked by yellow arrow).(e) NE dipping quartz vein showing slickenside lineations (maximum width recorded=120 cm), inset showing close up of the fault plane found in e. Marker pen placed along the orientation of the slickenside lineations. (f) Angular chunks of metabasalt (enclaves) enclosed within faulted quartz vein. Dotted red line demarcates the enclave boundaries. Black arrow marks the slickenside lineation on the fault plane. (g) Field photograph of quartz vein (close view) showing multiple median lines (marked with red arrows) as an evidence of crack- seal mechanism. This clearly indicates cyclic fluid ingression and fault valve action that led to the formation of veins in the metabasalts of the Chitradurga region. (h)Fault planes in metabasalt showing congruous steps (marked by yellow arrow). Blue arrow in the respective figures point towards N.

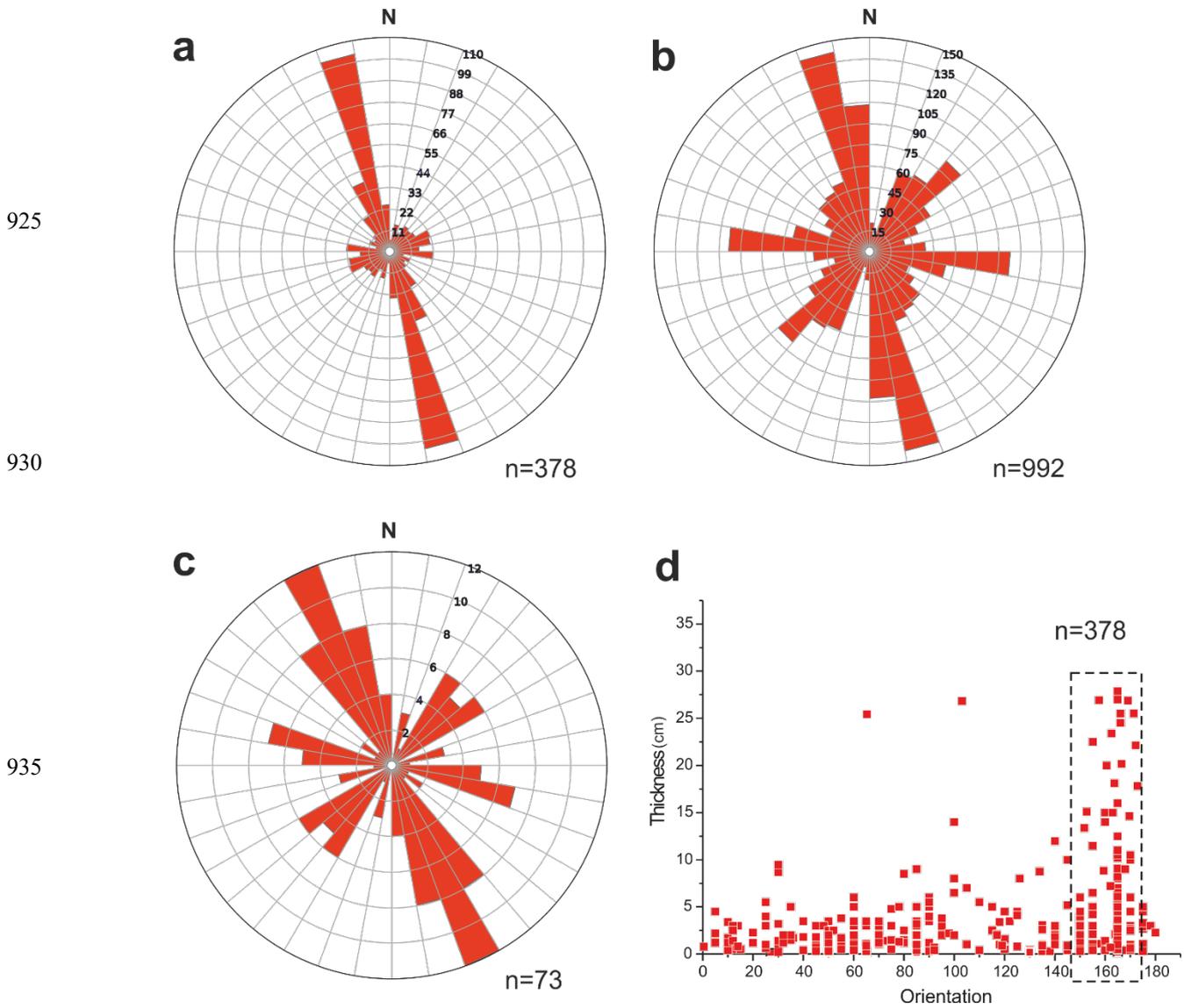



Figure 04. Rose diagrams and graphs of structural data recorded from the study area. (a), (b) and (c) are the rose diagrams of the strike orientation of the quartz veins, fractures and fault planes respectively. Note that the veins are mostly NNW-SSE striking whereas the fractures and fault planes show variable orientations, with a NNW-SSE maxima and a WNW-ESE to NE-SW sub maxima. (d) Graph of vein orientation vs. thickness, showing maximum vein thickness along NNW-SSE (marked with orange box). n= number of data.

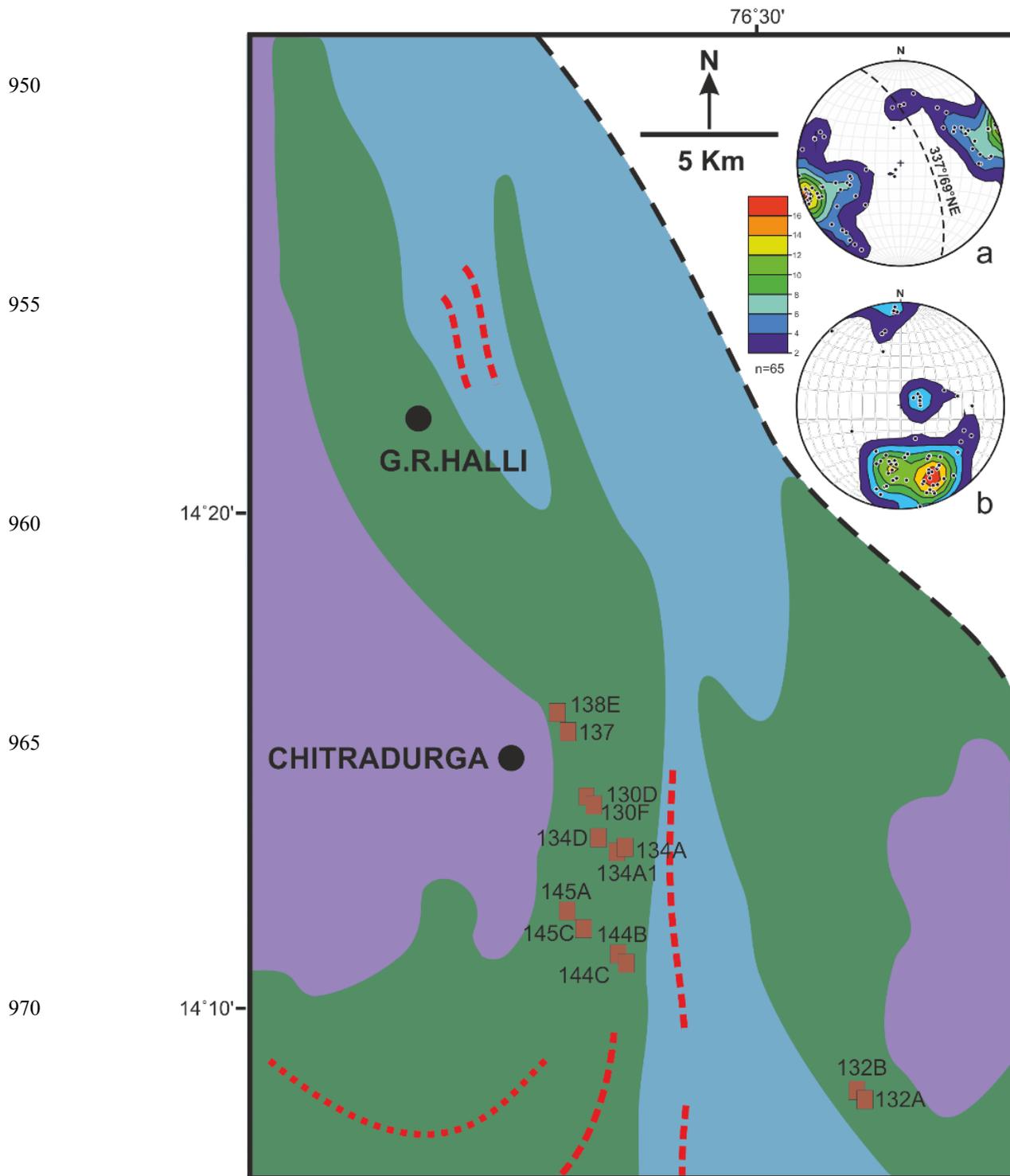



Figure 05. Map showing the location points (marked with brown boxes) from which oriented metabasalt samples for AMS analysis have been collected. (a) Lower hemisphere equal area projection of poles (K_3) to magnetic foliation (K_1K_2) plane. Mean orientation of K_1K_2 plane (dashed great circle)= 337º/69ºE (b) Lower hemisphere equal area projection showing the distribution of magnetic lineation (K_1).Color scheme of the legend indicates variation in the contour density.

Figure 06. Tensile strength determination of metabasalt samples. (a) Sample cores for Brazillian tensile strength (BTS) determination. Diameter: length=2:1. (b) Instruments used for measuring BTS. (c) Sample cores obtained after failure.

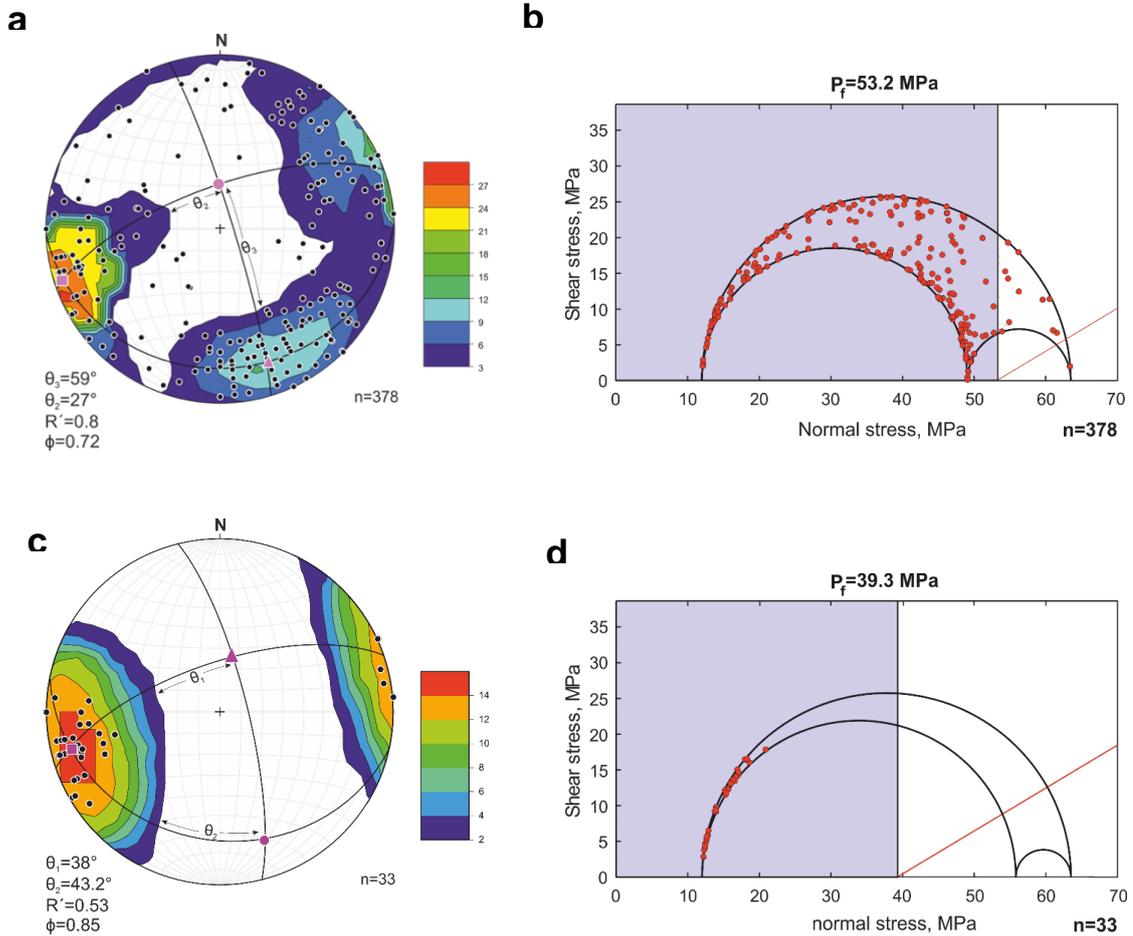



Figure 07. State of stresses and fluid pressure (P_f) conditions determined from vein orientation data in the study area. (a) Lower hemisphere equal area projection of pole to veins shows girdle distribution, implying $P_f > \sigma_2$ (following Jolly and Sanderson, 1997). The empty space devoid of any vein pole data helps to determine the position of σ_1 (using Bingham statistics of the Stereonet 9 software) and thereby defines $\sigma_1\sigma_2$ and $\sigma_1\sigma_3$ planes. Angles θ_2 and θ_3 are measured which are used to determine the stress ratio (ϕ) and driving pressure ratio (R') respectively. Color scheme of the legends indicate variation in the contour density. Pink circle (σ_1), pink triangle (σ_2) and pink square (σ_3) respectively. (b) 3D Mohr circle diagram for high P_f conditions. Red line in the Mohr circle represents the reactivation envelope for cohesionless fractures. Vein pole data lying within the blue zone, i.e., to the left of the P_f (black) line represent fractures filled up with veins that are susceptible to reactivate (Fractend code available via

Github, 2017). (c) Lower hemisphere equal area projection of poles to vein data forming the SW cluster in (a), this cluster distribution of vein pole data indicates $P_f < \sigma_2$. Cluster maxima defines σ_3 axis. Angles θ_1 and θ_2 are measured and similarly ϕ and R´ are determined. (d) 3D Mohr circle diagram for low P_f condition. Only a limited range of fracture filled up with veins are susceptible to reactivate. Red dots represent pole to vein data, red line forms the reactivation envelope for cohesionless fractures.

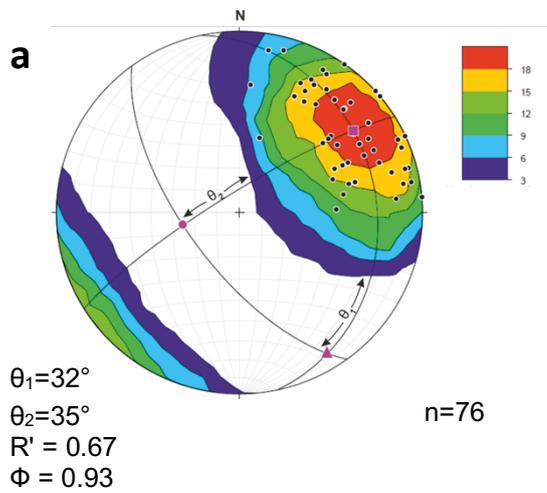
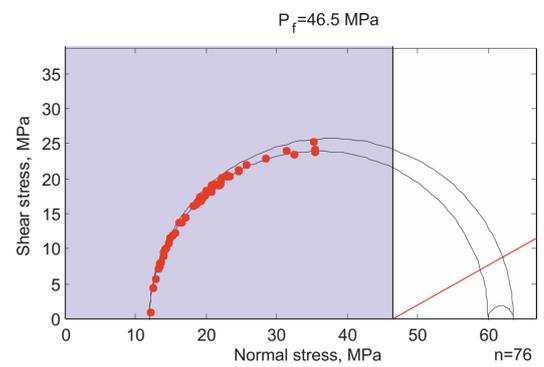
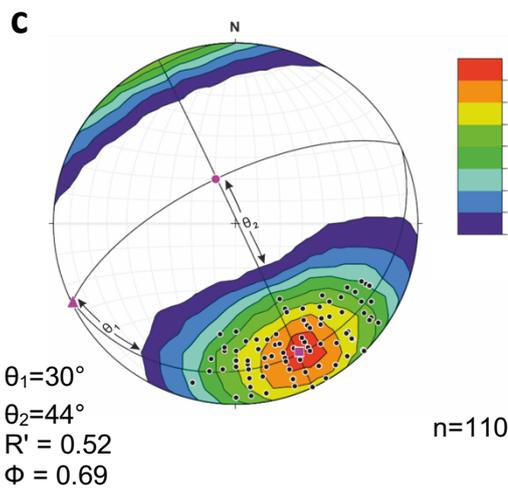
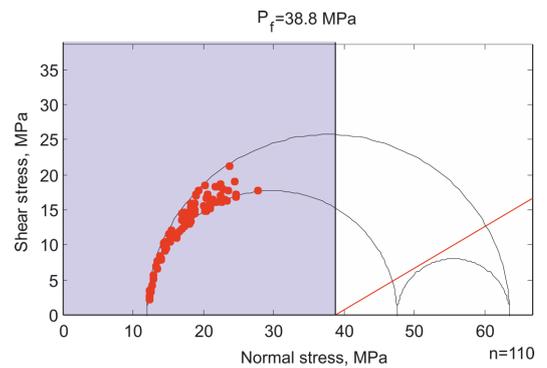



Figure 08. State of stress and fluid pressure (P_f) conditions determined from the vein orientation data in the study area. (a) Lower hemisphere equal area projection of poles to vein data forming the NE cluster. (b) 3D Mohr circle diagram for NE cluster. (c) Lower hemisphere equal area projection of poles to vein data forming the SE cluster. (d) 3D Mohr circle diagram for SE cluster. In the respective lower hemisphere equal area projections, cluster distribution of vein pole data indicates $P_f < \sigma_2$. Cluster maxima defines σ_3 axis. The ranges of fracture orientations (θ) are measured. Subsequently, ϕ and R' values are also determined similar to Fig 7. Pink circle (σ_1), pink triangle (σ_2) and pink square (σ_3) respectively. In the 3D Mohr circle diagrams, only a limited range of fracture filled up with veins are susceptible to reactivate. Red dots represent pole to vein data, red line forms the reactivation envelope for cohesionless fractures. Vein pole data lying within the blue zone, i.e., to the left of the P_f (black) line represent fractures filled up with veins that are susceptible to reactivate.

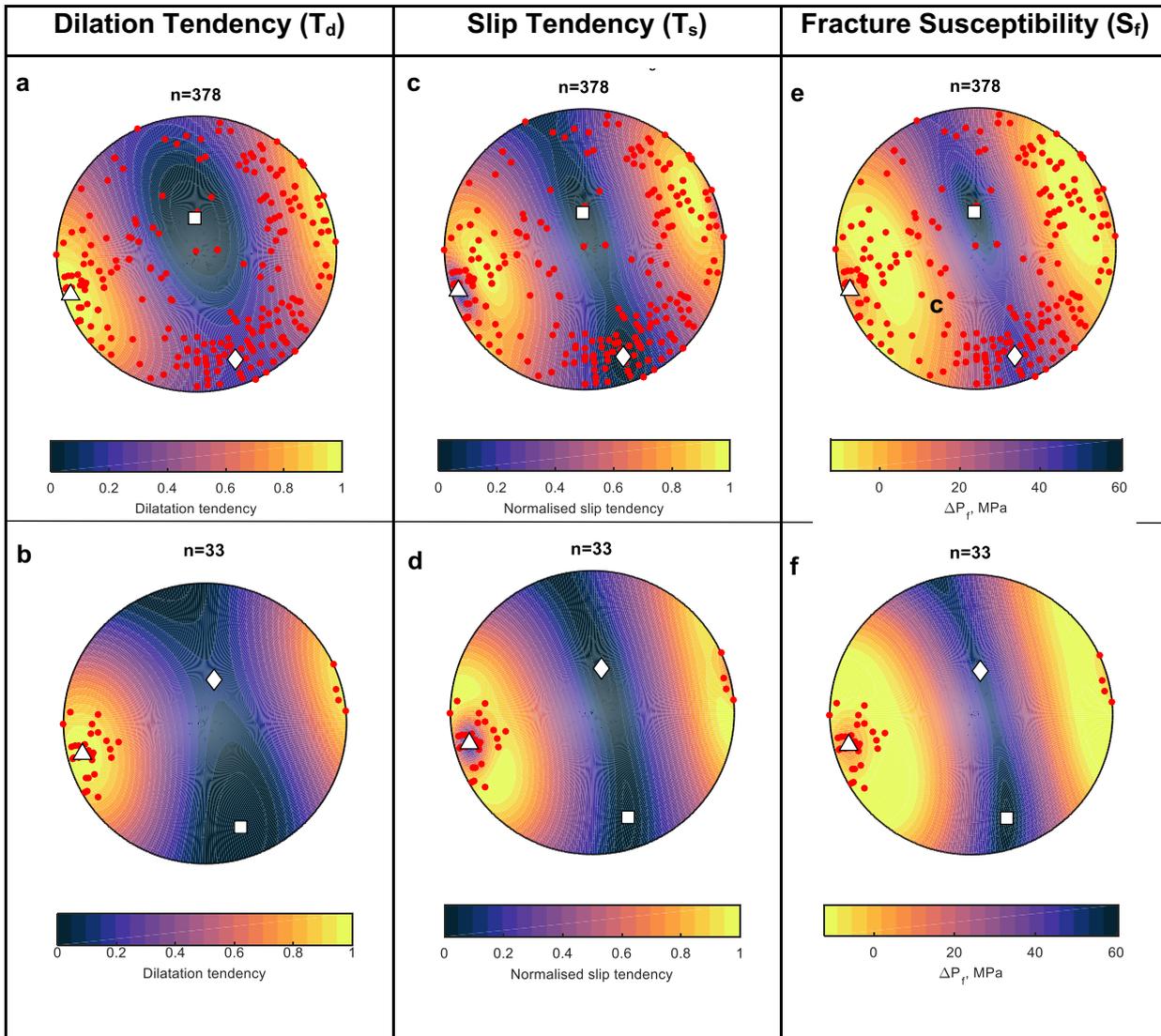



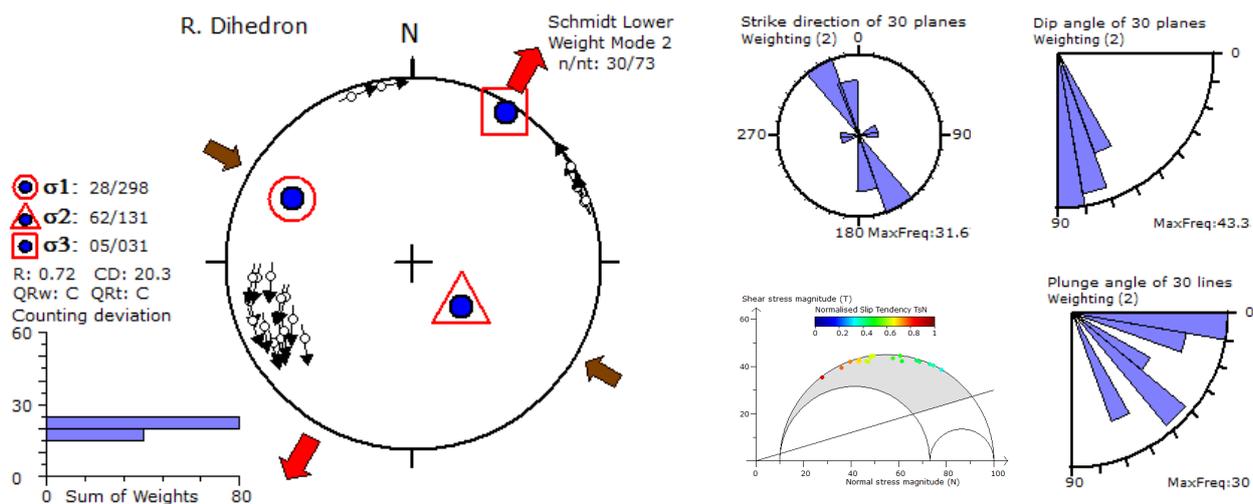
Figure 09. Lower hemisphere equal area projection for dilation tendency, slip tendency and fracture susceptibility in a given fluid pressure condition and for a specific stress state (Fractend code available via Github, 2017). (a) and (b) represents dilation tendency for high and low P_f. (c) and (d) represents slip tendency for high and low P_f. (e) and (f) fracture susceptibility for high and low P_f conditions respectively. Warm color zones in (a) and (b), represents vein orientations with higher propensity for tensional opening. In (c) and (d) warm colors indicate vein attitudes that suffered shearing. In (e) and (f) the warm color zones stand for vein attitudes that are more susceptible to reactivate under low P_f variation. 'Thermal' color scheme from Thyng et al., 2016. White square (σ_1), white diamond (σ_2) and white triangle (σ_3).

1145

Figure 10. Paleostress analysis (using right dihedron method) of faults recorded in the metabasalts of the study area; for both left lateral and right lateral normal faults. Red arrow marks the extension direction (σ_3) and pink arrow marks the principal compression direction. The histogram shows the minimum values for counting deviation. *n* and *nt* are the number of data accepted for tensor calculation and total number of data respectively. R (stress ratio) = $(\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$. Rose diagrams for fault plane strike, dip and plunge variations are also presented in the top right corner. 3D Mohr diagrams demonstrate possible areas of fault reactivation with variation in susceptibility, colored circles represent pole to the fault planes. The failure envelope for Mohr's circle is based on Byerlee (1978) initial friction angle of 16.7^0. Note that the maximum extension is along NNE-SSW direction.

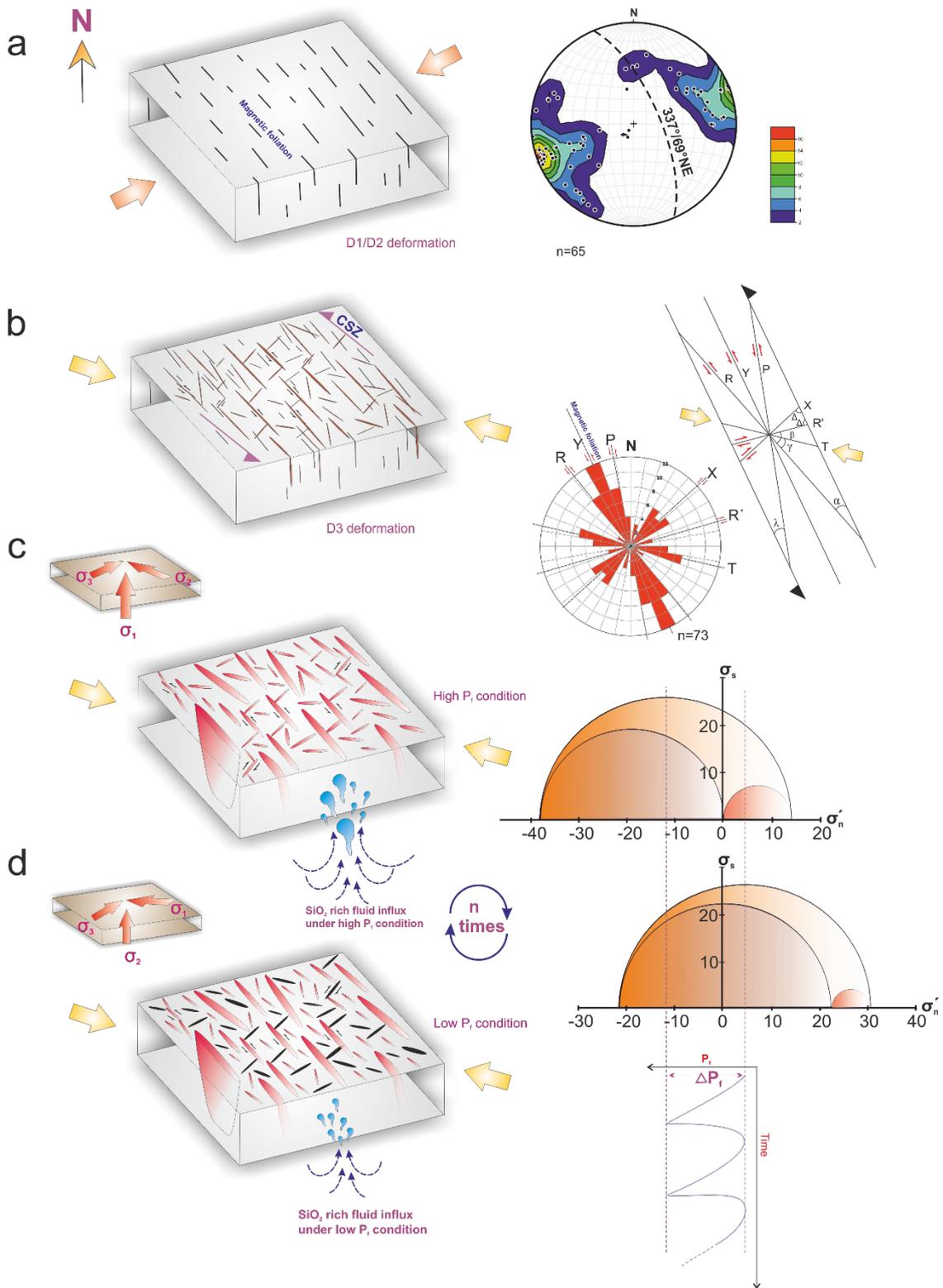



Figure 11. Schematic model showing formation and reactivation of fractures, along with vein emplacement in the metabasalt host rock. (a) Development of the NNW-SSE to NW-SE oriented magnetic fabrics in the rock unit under a NE-SW shortening related to D1/D2 deformation. Lower hemisphere equal area projection shows mean orientation of the magnetic fabric ~ 337º/69ºNE. (b) Formation of the Y, P, R, R′, X and T shears related to the riedel shear system under a NW-SE to E-W shortening related to the late D3 deformation (half arrows representing the shear zone boundary). The angles (α, β, γ, λ and Δ) between the shear components are given after Logan et al. 1992. $\Phi=30˚$ (angle of internal friction) is measured from UCS studies of the samples from the study area. Corresponding riedel shear model, with CSZ as the shear boundary and rose diagram showing orientations of the respective shear components. (c) and (d) showing vein emplacement under high P_f and low P_f conditions respectively (state of stresses along the fracture planes are given, in c, σ_1 is vertical due to fluid overpressure). Corresponding 3D-mohr circle diagrams quantifying the effective normal stresses ($\sigma_n' =\sigma_n$- P_f; in Mpa) under both high and low P_f conditions, difference in P_f (ΔP_f ~13.9 MPa), obtained from the dashed lines representing the mean stress in each case. A conceptual graph shows multiple cycles (n-times) of high and low P_f conditions in the study area justifying *fault-valve action* that led to the emplacement of vein in the Chitradurga region.