STUDY OF DEFORMATION PATTERNS OF ERINPURA GRANITES FROM PARTS OF RAJASTHAN AND ITS IMPLICATION

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Contents

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SUBHABRATA DAS

DEDICATED TO MY PARENTS AND MENTOR

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Certificate

This is to certify that Mr. Subhabrata Das has worked under my guidance and completed his thesis entitled "Study of deformation patterns of Erinpura granites from parts of Rajasthan and its tectonic implications" in the Department of Geological Sciences, Jadavpur University in partial fulfilment of his Master of Science Examination in Applied Geology of Jadavpur University in 2019.

Mr. Das has fulfilled all the prescribed requirements and this work has not been presented for any degree or diploma elsewhere.

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Abstract

The Marwar Craton is located in the west of Delhi Fold Belt (DFB). The Delhi Fold Belt (DFB) of northeast southwest trending, multiply folded and poly-metamorphosed rock of Proterozoic age. The western margin of the SDFB is demarcated by Phulad Shear Zone (PSZ) of mid-Proterozoic age (810 Ma), defining a contact between DFB and Marwar Craton. The PSZ is characterized by northeasterly striking ductile shear zone with a well developed mylonitic foliation and a down-dip stretching lineation. The Marwar Craton is dominated by a number of granites and granite gneisses and among them Erinpura granites are present in the vicinity of PSZ. The present study deals with the systematic study of these granites to understand its deformation pattern in relation to Phulad Shear Zone (PSZ).

The granite is a coarse grained, white to grey coloured and slightly to strongly deformed. The granite shows crude foliations to prominent well developed foliations with attitudes varying from NNW-SSE to NE-SW. The less deformed granites are present at places far away from PSZ and are showing crude tectonic foliations which are oriented parallel to the magmatic foliation defined by oriented euhedral phenocrysts. The highly deformed granites are showing highly deformed phenocrysts with asymmetric tail. These highly deformed granites are present at vicinity of PSZ where they are ultimately transforming into remobilized belt comprising of ultramylonite oriented parallel to PSZ. The granites present in between are showing characteristic oriented euhedral phenocrysts and deformed phenocrysts with asymmetric tails, both oriented in NNW-SSE and NE-SW repectively.

Systematic study of mesoscopic structures of these granites and the shear zone rocks demonstrate similarity in geometry and style. This indicates that the deformation in the granite and the shear zone is broadly synchronous.

CHAPTER 1

1.1. Introduction

The Delhi Fold Belt (DFB) of northwestern Indian shield is a NE-SW trending, 700 km long mountain chain consisting of multiple folded and poly-metamorphosed rocks of Proterozoic age. The western part of the DFB is defined by a narrow zone of intense deformation known as Phulad Shear Zone (Gupta et al, 1980; Sinha-Roy 1988; Golani et al. 1998; Ghosh et al. 1999). The Phulad Shear Zone (PSZ) separates the DFB to the east with the granites and granite gneisses of the Marwarcraton to the west (Sinha-Roy, 1999). The PSZ is recognized on the basis of extensive development of mylonite for a distance of 30 km or more (Ghosh et al, 1990; Golani et al, 1998) in a transpressional regime of ductile shear zone (Ghosh et al, 1999; Ghosh et.al, 2003; Sengupta and Ghosh 2004; Sengupta and Ghosh 2007). The strain of the shear zone is mainly concentrated along bands of interlayered calcareous and quartzofeldspathicmylonites. There are several reports of intrusive bodies, particularly granite, into the Delhi Supergroup that ranges from older than 1600 Ma to 850 Ma (Choudhury et al 1984, Crawford 1970, Gopalan et al 1984) but there is a lacuna of information about the spatial and temporal pattern of these granitic rocks. More or less Marwarcraton is dominated by the presence of large numbers of granites and granite gneisses and Erinpura granite is one among them which is defined by its porphyritic nature. The present study mainly concentrates on theErinpura granites which are located along the western margin of the South Delhi Fold Belt (SDF) in the vicinity of Phulad Shear Zone (PSZ), Pali district, Rajasthan. These granites are consisting of euhedralphenocrysts to deformed phenocrysts.The present study comprises a systematic study of these less deformed granites to extensively deformed granites which will aid in understanding its deformation in relation to the Phulad Shear Zone (PSZ).

1.2. Geological settings

The broadest geomorphic divisions of India are the Peninsular India, the extra- peninsular india and the Indo-Gangetic Plain which are also the three broadest tectonic divisions of India. The

Peninsular India comprises the Indian Shield and its Proterozoic and Phanerozoic covers. The Indian Peninsula comprises four major cratons viz., Dharwar, Bhandara, Singbhum and Bundelkhand that are bordered by the Aravalli-Delhi, SatpuraSingbhum and Eastern Ghat mobile belts. The Delhi-Aravalli fold belt is the northern crustal segment of the Indian peninsula trending northeast- southwest.

An analogy has been drawn from the stratigraphic order established in the northeastern Rajasthan by Heron (1953) who classified the Delhi system (now called Delhi Supergroup).

The Delhi Fold Belt (DFB) of northwestern Indian shield is a NE-SW trending, 700 km long mountain chain consisting of multiply folded and poly-metamorphosed rocks of Proterozoic age.

The rocks of the Delhi fold system are middle to upper Proterozoic in age. The Delhi Fold Belt occurs in two belts namely,

1) The North Delhi Fold Belt (NDFB)
2) The South Delhi Fold Belt (SDFB)

The SDFB is developed along the Aravalli hill range in central Rajasthan. The rocks of the SDFB are deposited in two sub-basins. The eastern sub basin contains rocks of the Barotiya and the Sendra groups which contain basic and felsic volcanics. The contacts between the different sequences are defined by prominent ductile shear zones and the thrusts (Gupta et al 1980).

The western part of the DFB is defined by a narrow zone of intense deformation known as Phulad Shear Zone (Gupta et al, 1980; Sinha-Roy 1988; Golani et al 1998; Ghosh et al. 1999). The Phulad Shear Zone (PSZ) separates the DFB to the east with the granitoid and gneisses of the Marwar Block to the west of Rajasthan (Gupta et al. 1980; Sinha-Roy 1988, 1999; Golani et al. 1998; Ghosh et al. 1999; Sengupta and Ghosh 2004, 2007).

1.3. Lithostratigraphy

Basement Rock

The basement rocks of Rajasthan are referred to as Banded Gneissic Complex (BGC) (Heron, 1953), where it is best exposed in the south of Mewar. These BGC essentially contains igneous rocks and multiple cycles of metasediments that form banded composite gneiss. Zircons derived from the basement gneiss yielded an age of 3.5Ga age (venkobarao et al., 1958) suggesting an Archean age for the gneisses. This has been further supported by the age of Untala granites (2.9Ga) which are intrusive within the BGC (Chaudhary et al. 1981).

The pre-Aravalli basement is made up of five sequences as follows:

1) Bimodal gneisses containing alternate bands of tonalite/granodiorite and orthoamphibolites.

2) The intrusive granite bodies within the pre-Aravalli basement are Untala and Gingla granites (2.96 Ga) and Berach Granite (2.6 Ga).

3) Two pre-Aravallisupracrustal sequences:

    a) An older greenstone like sequence consists of discontinuous bands and patches of ultramafic bodies, amphibolites, peliticschists, calc silicate rocks,chert graphite schist and metagreywacke.

    b) A younger greenstone named as Hindoli Group consists of mafic to felsic volcanic in the lower part and metagraywacke and meta-pelites. The Hindoli Group sequence is now considered as early Proterozoic since its basement Berach Granite is dated 2.6 Ga.

The three sequences (1, 2 and 3a) are grouped together and named as Mangalwar Complex.

4) The granulite facies rocks occurs as tectonic wedges within BGC near Sandmata known as Sandmata complex and consists of garnet-sillimanite gneiss, enderbite and

charnockite, two pyroxene granulite, leptynite and cordierite-garnet gneiss. The enderbite- charnockite occurs as intrusive pluton within the granulite gneiss and the emplacement of charnockite took place at 1723 Ma. (U-Pb age).

Aravalli Supergroup

Meta volcanic and Meta sedimentary rocks are associated with AravalliSupergroup. A 200 Km long belt of the rocks of AravalliSupergroup varies in width from 10 km in the north to 70 Km in the south. The AravalliSupergroup can be classified as lower, middle and upper Aravalli group (Roy, 1988; Roy and Jakhar, 2002). Conglomerate and red beds observed at the unconformable contact of these three groups. Marble and associated rocks which were considered previously in Raialo series by Heron (1953) is now included in AravalliSupergroup (Naha and Halyburton, 1974; Naha and Majumdar, 1971a; Naha et al., 1973; Roy et al., 1984; Roy and Paliwal, 1981). Quartzite, Arkose and Conglomerate bodies which were considered as outlier of Delhi system by Heron (1953), are also now included in AravalliSupergroup (Poddar, 1965; Roy et al., 1984; Roy and Paliwal, 1981). Bhilwara belt and the Udaipur-Jharol belt are two major adjoining belts situated in AravalliSupergroup. The Udaipur-Jharol belt is exposed as an inverted "V" shaped area with tapering end near Nathdwara. Two contrasting sedimentary facies association has been distributed along roughly north-south trending UdaipurJharol belt at the type are of AravalliSupergroup. According to Roy and Paliwal (1981), two segments of Paleoproterozoic coupled basin representing the Udaipur Jharol belts. Polymictic conglomerate overlain by quartzite, mafic and ultramafic volcanic rocks are marked as base of shallow water Udaipur sub basin (Ahmad and Rajamani, 1991) whereas inter-layered volcanic and quartzite serve as base of the deep water Jharol sub basin (Gupta et al., 1980). Chronological data by several worker suggested that the basal Aravalli volcanism happened during 2.3-1.8 Ga (Deb and Thorpe, 2004; Ahmad et al., 2008). The two litho-facies such as self facies and deep sea facies representing eastern and western arm of the Udaipur-Jharol belt respectively. The eastern side of the belt, composed of shale-sand-carbonate assemblage, representing near shore self-facies whereas a thick sequence of carbonate free shale inter bedded with thin beds of arenites found in the western side of the belt, representing deep-sea facies (Roy and Paliwal, 1981). Rakhabdev lineament is considered as a tectonic contact, which divide the Udaipur-Jharol belt into two facies. Mafic and ultramafic rocks associated with quartzite band have been observed along the north-south trending lineament. Udaipur region is considered as the type area of AravalliSupergroup, where the rocks were deposited during Paleoproterozoic age (2.5-1.6 Ga). Complex pattern of deformation observed in the rocks of AravalliSupergroup. Polyphase deformation mainly three major phases of folding F1, F, and F3 and associated shearing is observed in the type area. Low grade metamorphism took place in the entire Aravalli rocks around Udaipur region (Roy, 1988; Sharma, 1988). High grade metamorphic rocks were found near Katar and Bagrunda, located at the fringe of Delhi fold belt. High grade rocks also found near Salumber and Bhukia, located south-east of Udaipur.

Delhi Supergroup

Delhi Supergroup was previously believed Delhi system composed of arenaceous and argillaceous rocks unconformably overlies the Delhi system (Heron, 1953). The Delhi Supergroup is the backbone of Aravalli Mountain Range as it extends all along the mountain range from Delhi in the north to Himmatnagar in the south. Beyond Himmatnagar the solid rocks of Delhi Supergroup is lost due to overlapping the alluvium cover. It is narrow of about 10 Km at the central part and wider toward the two ends. In the northern side the width of the Delhi Supergroup is about 200 Km along Khetri-Bayana-Alwar track. Based on litho-facies assemblages, Delhi system has been divided into two series such as lower Alwar series and upper Ajabgarh series (Heron, 1953) which are now referred as group. The name 'Delhi system' has changed to 'Delhi Supergroup' by Gupta et al., (1980) in their revised map of 1:50,000 scale. Alwar group is characterized by the presence of arenaceous rocks such as schists, phyllites, amphibole quartzite, arkosic quartzite, marble etc. Argillaceous and calcareous types of rocks are dominated in Ajabgarh group with large amount of volcanic products. Some workers has questioned on this simple classification of Delhi Supergroup (Dasgupta, 1964; Sen, 1981). The Delhi belts have further been classified into two segments named North Delhi Fold Belts (NDFB) and South Delhi Fold Belts (SDFB). North Delhi Fold Belts is considered to the north of Ajmer whereas South Delhi Fold Belts is representing the rocks of south of Ajmer (Dev and

Sarkar, 1990; Sinha-Roy et al., 1998). This classification was based on the nature of mafic and ultramafic rocks, volcanic and sedimentary ratio, period of granitic intrusions, base metal mineralization and related sulphur and lead isotopic ratio. From north to south the rocks of Delhi Supergroup believed as continuous by some geoscientist based on continuous lithostratigraphy (Singh, 1988a), similar metamorphic pattern (Sharma, 1988) as well as similar structural history (Naha et al., 1984). Multiple phases of folding are present in Delhi Supergroupviz DF1, DF2 and DF3 (Naha et al., 1984, 1987; Sychanthavong and Merh, 1985). The sedimentary and volcanic rocks of the Delhi's are found to have recrystallized first under regional metamorphism (up to amphibolite facies), which was later superimposed by the thermal metamorphism (homblende-homfelsfacies). Delhi Fold Belt has evolved due to rifting. It is also suggested that the Delhi Fold Belt was evolved by the formation of rifts in the North Delhi Fold Belt and preceded in ocean opening in the South Delhi Fold Belt. Several granitic bodies are observed in Delhi Supergroup such as Sendra granite, Erinpura granite, Kishangarhsyenites, Ambaji granites.

South Delhi Fold Belt

The southern part of the Delhi Fold Belt is considered as South Delhi Fold Belt which traverses from Abu road in the south to just north of Ajmer. The belt is composed of carbonate facies rocks, mafic plutonic rocks such as gabbro, and leucogabbro, mafic-ultramafic volcanics and felsic volcanics. The age of felsic plutonic rocks is ranges between 850 to 750 Ma (Gopalan, 1986). Along the entire South Delhi Fold Belt, an Ophiolitic association is present as a linear zone and the ophiolitic association is composed of layered gabbro, pillow basalts, pyroxenite, serpentinites and sometimes sheeted dykes and andesites. According to Sharma (1988), regionally the rocks of South Delhi Fold Belt are metamorphosed up to amphibolitesfacies although in the northern part of the belt green schist facies of metamorphism is observed.

North Delhi Fold Belt

Three sedimentary sub-basins together constitute the North Delhi Fold Belt (NDFB). From east to west these sub-basins are i) Bayana sub-basin ii) Alwarsubbasin and iii) Khetri Sub-basin (Singh, 1988). Grabens are formed in the gneissic basement to develop the sub-basins and sedimentation was largely controlled by vertical tectonism. The volcano-sedimentary infills have divided into Alwar and Ajabgarh group in every sub basin (Heron, 1953). In the beginning carbonate shelf sediments deposited followed by coarse clastic sediments of Alwar group (Singh, 1988b). Multi-lagoonal tidal flats are responsible for Ajabgarh sedimentation. Shallow marine environment for sedimentation of Khetri area has been proposed by Dasgupta (1968) and Sarkar and Dasgupta (1980).

1.4. Supracrustal Lineations

Deep dislocation zones of crustal scale are marked by ductile shear zones, both at the boundaries and within the domain (Sinha-Roy, 1984; Sinha-Roy et al., 1995). The basal Aravalli succession is present against the basement complex along the unconformity. Described as the Delwara Dislocation Zone, it is traceable along the interface of the basement. The Banas Dislocation Zoneforms the eastern boundary of the Aravalliterrane. The western boundary of the southern Delhi domain or the South Delhi Fold Belt (SDFB) is defined against the basement to the Marwarcraton in the west is defined by the Phulad Dislocation Zone and in the eastern part against the Aravalli by the Kaliguman Dislocation Zone. In its southern part, the Delhi domain is split by imbricatingfault zones. The basement rocks have been thrust up and emplaced as wedges within the overlying sedimentary piles. The Rakhabdeo Suture Zone comprises tectonizedserpentinized bodies of gabbro and ultrabasics, marking a separation between the deepwaterfacies of the Aravalli succession and the platform sequence of the Aravalli succession. The Great Boundary Fault defines the eastern limit of the Aravalli Mobile Belt or the Aravalli Fold Belt (AFB) against the Vindhyan domain. It is a reverse fault which has shown movements within a hinge area located 20 km north of Chittaurgarh. It is a system of parallel faults which at places joins to form a single major fault plane. It registers maximum throw of 1300–1400 m in the Mandalgarharea (Tiwari, 1995). Here, the Rewa of the Vindhyan is present against the Banded Gneissic Complex (BGC), the throw gradually decreasing southwards to merely 150–200 m at Khardeola (Verma, 1996). It is thought to have evolved as a normal fault 2500 million years ago, but acquired its reverse geometry during the Delhi orogeny or the Delhi Fold Belt(DFB) 1400 million years ago (Valdiya, 2016).

<table>
<tr><td colspan="2">Heron (1953)</td><td colspan="2">Gupta et al. (1980)</td><td colspan="2">Roy and Jakhar (2002)</td></tr>
<tr><td colspan="2">Malani Series
Erinpura granite</td><td>Proterozoic-III</td><td>MarwarSupergroup
Malani suite
Erinpura granite and gneiss
VindhyanSupergroup</td><td>MarwarSupergroup
Malani Group = Sindreth Group
(780–680 Ma)
Granite of Erinpura, Pali, etc. 835 Ma
Sirohi Group
Intrusion of gabbro, diorite (1000 Ma)</td><td rowspan="2">Vindhyansupergroup</td></tr>
<tr><td>Delhi System</td><td>Ajabgrh Series
Alwar Series
Railo Series</td><td>Delhi Supergroup 2000–740 Ma
Proterozoic-II</td><td>Punagarh Group = Sindreth Group
Sirohi Group = Sendra, Ambaji granite
(ca. 800 Ma)
Kumbhalgarh Group = Aajbgarh Group
Gogunda Group = Alwar Group</td><td>Synorogenic granite (1400 Ma)
Delhi Supergroup</td></tr>
<tr><td colspan="2">Aravalli System</td><td colspan="2">AravalliSupergroup (2500–2000 Ma)
Proterozoic-I</td><td colspan="2">Darwal granite (1850 Ma)
AravalliSupergroup</td></tr>
<tr><td colspan="2">Banded gneissic complex (BGC)</td><td colspan="2">BhilwaraSupergroup
Archean</td><td colspan="2">Untala, Ahar, Berachgranitoids (2500 Ma)
Mewar gneiss (Heron’s BGC) (2600–3300 Ma)</td></tr>
</table>

Precambrian Stratigraphy of Rajasthan (Sharma, K. K., 2005)

1.5. Erinpura Granites

During Neoproterozoic era, south western flank of the Aravalli Mobile Belt and further western terrain from it witnessed emplacement of granites and felsic volcanism. These plutonic bodies giving nearly concordant dates between 750 ma and 900 ma are known as Erinpuragranite.Compositionally it has been said to be of granodioriticto granitic in nature.It is said to be of anorogenic origin and variable texture throughout.

1.5.1. Naming and status

Initially, Erinpura granite is named for the granites of type area Erinpura (presently known as Sheoganj, Sirohi district) (La Touche, 1902). Erinpura granite has been correlated to Abu granites (Mt. Abu) on the basis of physical continuity (Coulson,1933) and on the basis of terminal stage of felsic magmatism forming late synorogenic to post orogenic granites and granodioritesthroughout the southern sector of the Delhi Fold Belt and it's western foreland (Heron,1953).Erinpura granite has been said to be an ensemble of variably deformed granites and granite gneisses (Gupta et al, 1997). Granites of Isra and Andor in Sirohidistrict,Rajasthan are designated as Erinpura granite and are stated as mainly S-type granites (Banerjee et al,1998; Maithani et al,1998 ,2000,2008).

1.5.2. Age

The Neoproterozoic granites are present throughout andare dated for different locations.Erinpura granites of Sirohi and adjoining areas have yielded an isochron age of 740 ma (Crawford, 1970). Granites in Godhra area is dated at 900 ma (Gopalan et al, 1979).Younger granites dated at 830 ma by whole rock Rb-Sr dating (Chowdhury et al, 1984).Erinpura granite yielded an isochron age of 740 ma (Pandey et al ,1995; Chabria et al,1997).Younger Erinpura granite yielded an age of 800-900 ma by U-Pb zircon dating (Deb et al,2001).Tonalitic to granitic plutons cutting through the Delhi rocks in the Sendra area are dated at 906 ± 6.1 ma by Rb-Sr whole rock isotopic dating and 967 ± 1.2 ma by U-Pb zircon data (Pandit et al, 2003.a).Monazite grains of metamorphic rocks of Mangoli Complex are dated by electronmicroprobe method at 946 ± 6.9 ma and the granites intruding metamorphic rocks are dated at 978 ± 18 ma(Bhownik et al, 2010). Dating of structurally controlled monazite gave age of 870-830 ma (Jana et al, 2010). Erinpura granites of type area Erinpura are dated at 863 ± 23 ma by U-Pb dating and with electron microprobe method of monazite, 775 ± 26 ma by U-Pb dating and with electron microprobe method of monazite along the shear zone granites (Just et al, 2011).Erinpura suite have shown an age of 800-900 ma by U-Pb zircon dating (Van Lente et at, 2009; Solanki, 2011).Granites of Dosai, Khetri Belt are dated at 1700-1720 ma and associated metasomatisedmafics are dated at 831 ± 15 ma by Sm-Nd whole rock isochron age (Kaur et al, 2013).

1.5.3. Geochemistry

Initially, meta-sedimentary protolith was considered as a source to Erinpura granites (Gangopadhyay and Lahiri, 1984). Erinpura granites have been divided into BaldaLeucogranite (BLG) and Erinpura granite (ERG). The major element geochemistry shows ERG has low SiO_2, higher TiO_2,MgO and CaO than BLG. BLGis considered to be peraluminous .Trace element geochemistry shows that the mean value of ERG and BLG indicated an increase in Nb, B, Be, Li and Rb and depletion of Sr and Ba from ERG to BLG. W content increases from metasediments to BLG and Ti content decreases from ERG to BLG (M.S.Naik, 1993).Erinpura granite is considered to be an overlap of I-type and S-type granites indicated an igneous protolith (Bhushan, 1995). Later it has been suggested that Mt. Abu granitoids were produced by variable mixing with mafic magmas resulting in Erinpura granite suites (Zorpi et al, 1989; Metcafe et al, 1995).

1.6. Study area

1.6.1. Location and Accessibility

Erinpura is a village in the Rajasthan state of India. It is located in the Sheoganj Tehsil of the Sirohi district. It is located near the Jawai Bandh station. It is located at an elevation of 286 meters above mean sea level (MSL). The area is well connected by a network of roads and railways. The NH-62 is the main lifeline for road communication to this area. The area is served by the meter-gauge network of North-Western Railways. Jodhpur and Jaipur are the only civic airports in the area. The M.Sc. Dissertation work is mainly composed of detailed study of emplaced granites of the western part of South Delhi Fold Belt (SDFB) which was earlier stated as Erinpura granite.

Coordinates: 25.141244°N 73.057444°E in DMS (Degrees Minutes Seconds).
Its UTM position is CH17 and its Joint Operation Graphics reference is NG43-09.

1.6.2. Climate

The Climate of Erinpura in northwestern India is generally arid or semi-arid and features fairly hot temperatures over the year with extreme temperatures in both summer and winter. The study area comes under tropical,warm climatic zone and moreover it is in vicinity of Thar Desert in NW Rajasthan and the area suffers a large diurnal variation in temperature. The temperature reaches upto 45°C during summer and in winter the temperature falls as low as 10° C. Erinpura receives low and variable rainfalls and thereby is prone to droughts.

1.6.3. Physiography of the study area

The territory which the state covers has developed after years of denudation and erosion processes and has a very mature topography. The State can be divided into two major divisions structurally along the Aravalli range which cuts the state into East Rajasthan and West

Rajasthan. These two divisions on the physiographic basis stretch into two of India's major physiographic divisions i.e. the Great Plains and the northern part of the Central Highlands respectively.

On the basis of the existing relief features and study of geomorphic evolution of the terrain, which has been sculptured through number of erosional cycles represented by various surfaces, the area has been divided into the following physiographic divisions:

1. Western Sandy Plains (a) Sandy Arid Plains- (i) Marusthali, (ii) Dune free Tract, (b) Semi-Arid Transitional Plains (Rajasthan Bagar)- (i) Luni Basin (Godwar Tract), (ii) Plain of Interior Drainage (Sekhawati Tract).

2. Aravalli Range and Hilly Region- (a) Aravalli Range and Bhorat Plateau, (b) Northeastern Hilly Region.

3. Eastern Plains- (a) Banas Basin, (b) Chappan Plains.

4. Southeastern Rajasthan Pathar- (Hadoti Plateau) (a) VindhyanScarpland,(b) Deccan Lava Plateau.

The region is characterised by mature topography with more or less flat topped mountain ridges, escarpment and vast stretches of plains. The whole area is undulating in nature and dominated by hilly terrains.

1.7. Objective of the study

2. To document the mesoscopic and microscopic structure of the granitic rocks.
3. To reconstruct the field structure of granitic rocks in relation to the tectonic deformation of the Shear Zone.
4. To document the deformation mechanism of the granitic rocks,bothmesoscopically and microscopically.
5. To use the textural and structural study for understanding the emplacements of these granites.

CHAPTER 2

2.1. Shear Zone

A shear zone is a zone in which strain is higher than in the wall rock, and whose margins are defined by a change in strain, typically seen by rotation of preexisting markers or formation of a new fabric (Earth-Science Reviews, 2017) i.e. in addition to the simple shear there is a component of pure shear across the shear zone (Manideepa Roy Choudhury, Subhrajyoti Das, Sadhana M Chatterjee, SudiptaSengupta; 2016). Shear zones and faults sharply delimit the cratonic block against the mobile belt (K.S. Valdiya, Jaishri Sanwal, in Developments in Earth Surface Processes, 2017).

2.2. Phulad Shear Zone

The Phulad Shear Zone (PSZ) in northwestern India represents the boundary between the western margin of Delhi Fold Belt (DFB) and eastern part of the Marwar Craton where variably deformed Neoproterozoic granitoids are present. ThePhulad Shear Zone (PSZ) of Rajasthan is a long narrow zone of intense deformation, running in a northeasterly direction for several kilometers and demarcates the western margin of the Proterozoic Delhi Fold Belt (Heron 1953; Sychanthavong and Desai 1977; Gupta et al. 1980; Sen 1980; Sinha Roy 1988; Sinha Roy et al. 1993; Gupta et al. 1997; Golani et al. 1998; Ghosh et al. 1999). The Phulad Shear Zone is essentially a NE–SW-trending shear zone. The deformation in the PSZ has developed in a transpressional regime with thrusting sense of movement .i.e.a type of strike slip deformation that deviates from simple shear because of a simultaneous component of shortening perpendicular to the fault plane. This movement ends up resulting in oblique shear. Transpression that occurs on a regional scale along plate boundaries is characterized by oblique convergence.More locally, transpression occurs within restraining bends in strike-slip fault zones (Dewey, J. F.; Holdsworth, R. E.; Strachan, R. A. (1998-01-01). "Transpression and transtension zones". Geological Society, London, Special Publications. 135 (1): 1–14).

Phulad Shear Zone is characterised by extensive development of mylonite for a distance of 30 km or more (Ghosh et al, 1990; Golani et al, 1998) with a distinctly sub-vertical stretching lineations (Ghosh et al 1999). The kinematics of the PSZ is identified as a transpressional setting (Sengupta and Ghosh 2004, 2007). The sense of movement in the shear zone is top to the west. In the present study the characterization of shear zone and chnges of lithology and structure across the western margin of the South Delhi Fold Belt in Pali district of Rajasthan is observed.

Phulad Shear Zone is having an overall trend of NE-SW in and around Pali District, Rajasthan. The Marwar Craton is located in the west of Delhi Fold Belt (DFB) and the contact between Marwar Craton and Delhi Fold Belt is demarcated by Phulad Shear Zone (PSZ). The areas of Marwar Craton in the vicinity of Phulad Shear Zone (PSZ) is dominated by a number of granites and granite gneisses and among them Erinpura granite is of porphyritic nature where phenocrysts of alkali feldspar is present in a matrix of quartz, feldspar, biotite and muscovite.

2.3. Field Relations

These granites are mainly showing four variations:

1. Less deformed

   Erinpura granites which are present far away from the Phulad Shear Zone (PSZ), horizontal section of these granites show euhedral phenocrysts which are aligned (Fig 2.2 a). These aligned euhedral phenocrysts when plotted in a rose diagram, the rose diagram is giving a mean resultant value of 156^0-336^0(Fig 2.2 b). At places, the horizontal section of these granites show crude foliations which are more or less parallel to the aligned euhedral phenocrysts of alkali feldspar in these granites (Fig 2.2 d). On plotting these crude foliations, stereographic projection is giving a principle foliation value of $156^0/84^0$W (Fig 2.2 e). In another section which is parallel to the planes of foliations show prominent downdip stretching lineations (Fig 2.2 c) and on plotting these stretching lineations in the stereographic projection, the stereographic projection is giving an attitude of $56^0 \rightarrow 169^0$ (Fig 2.2 e). The euhedral phenocrysts are measured along its length and width and they show a variation from 2cm to 6cm in length and a width variation of 0.2cm to 3cm in the horizontal section (Fig 2.3 a). Whereas in vertical section (Fig 2.3 b), these phenocrysts are also measured in terms of length and width and the aspect ratio is determined in both the cases of horizontal (Fig 2.3 c) as well as vertical section (Fig 2.3 d) and an aspect ratio vs frequency graph is plotted where aspect ratio is seen to be varying from 3 to 4.

2. Slightly deformed

Closer to Phulad Shear Zone (PSZ), the Erinpura granite in horizontal section shows two sets of phenocrysts: euhedral as well as deformed phenocrysts (Fig 2.4 a). The rose diagram of Erinpura granite exposed in this horizontal section shows a bimodal distribution (Fig 2.4 d). Euhedral phenocrysts are seen to be oriented in NNW-SSE direction when their orientations are plotted in a rose diagram (Fig 2.4 b) whereas the deformed phenocrysts which have formed tails in their extreme points along their lengths are showing a mean direction of NE-SW in a rose diagram (Fig 2.4 c).

3. Highly deformed

In the vicinity of Phulad Shear Zone (PSZ), granitic foliations are very prominent and the phenocrysts are highly deformed and no euhedral phenocrysts are present (Fig 2.4 e). These foliations are found to be changing its orientation from NNE-SSW to NE-SW (Fig 2.4 e). Overall the granitic foliations are showing broad warps and these granitic foliations are transformed into remobilized belts which are oriented parallel to the trend of Phulad Shear Zone (PSZ).

4. Ultramylonite variety

At Phulad Shear Zone (PSZ), the Erinpura granite is showing prominent foliation which is ultimately transformed into a remobilized belt comprising mainly of ultramylonite which is oriented parallel to the PSZ and the phenocrysts are completely deformed. This ultramylonite belt is dark grey in colour and is very fine grained in nature (Fig 2.4 f).

These ultramylonite belt shows prominent mylonitic foliations and lineations. On plotting these lineations and foliations in stereographic projection, the mean value of foliation and lineation is coming at $34^0/66^0$E and $65^0 \rightarrow 153^0$ respectively (Fig 2.5).

CHAPTER 3

3.1. Petrography

The granites are medium to coarse grained and show typical hypidiomorphic texture with large phenocrysts of alkali feldspar. The essential minerals consist of quartz, alkali feldspar andplagioclase while biotite, muscovite are the accessory minerals. Some samples show biotite and muscovite can also be a mojor phase. Some opaque minerals are also present. Modal composition of these granites show: 35 % quartz, 40 % alkali feldspar, 15 % plagioclase 5 % biotite, 5 % muscovite and some accessory opaque minerals.

Quartz shows anhedral shape with minor strain effects, and at places slightly fractured in nature. At places quartz grains have inclusion of plagioclase in them with sharp grain boundaries.

Alkali feldspar is mainly represented by Na-feldspar antiperthite, mesoperthite and orthoclase perthite (Fig 3.1 d). Alkali feldspar mainly occurs in occur in subhedral form and show mild sericitisation along the cleavage traces giving rise to hazy appearance. Besides, flame and vein perthites are seen following the cleavage planes and occasionally dominatingover the K-feldspars. Plagioclase is albite-oligoclase type, subhedral, moderately sericitised. At places, sericitised plagioclase patches are enclosed in K-feldspar phenocrysts. Biotite is present in two types of association with muscovite; samples which have thick muscovite bands have disoriented smaller sized biotites in it with relatively coarser grains of quartz in these bands whereas in some samples smaller disoriented grains of muscovite in thick biotite clusters are present.

The deformed porphyritic granite away from the shear zone is very coarse grained and characterized by large porphyroclasts of feldspar (plagioclase, K-feldspar and microcline) within a groundmass of medium grained assemblage of quartz, feldspar and fabric defining biotite and muscovite flakes. These porphyroclasts varying in size from 2cm to 6cm and show evidence of intracrystalline deformation. They show strong undulose extinction with prominent subgrain boundary, deformation lamellae and deformation twining. Feldspar clasts show effect of sericitization and also some brittle fractures. Inclusion of biotite, muscovite and elongated quartz are common within these clasts. Matrix is constitute of medium grained weak shape-preferred orientation of quartz-feldspar aggregates and elongated biotite and muscovite flakes which served as fabric defining element. In some places muscovite flakes show kinking and bending. Quartz and feldspar grains within the matrix also show evidence of intracrystalline deformation as well as dynamic recrystallization and recovery. Both quartz and feldspar grains show strong undulose extinction, deformation lamellae and development of small independent new grains by bulging of grain boundary into the older host grain which suggests bulging (BLG) recrystallization (Fig 3.1 c). Large subgrains with prominent straight boundary and chessboard subgrains are common within quartz which indicates rapid recovery at a higher temperature (more than 650°C). Lobate grain boundary between quartz - feldspar and pinning microstructure of mica and quartz suggest that this rock has been deformed at high-grade metamorphic conditions and they suffered grain boundary migration (GBM) recrystallization (Fig 3.1 a). Symplectite microstructure of quartz and feldspar and flame perthite are present. At places, new grain boundaries are forming by progressive rotation of subgrains suggesting a sub-grain rotation (SGR) type of dynamic recrystallization (Fig 3.4 b).

CHAPTER 4

4.1. Conclusion

The granites which are situated far away from the Phulad Shear Zone (PSZ) exhibits euhedral phenocrysts which are oriented 156^0-336^0. These euhedral phenocrysts both in horizontal and vertical section shows aspect ratio variation from 3 to 4 which indicates a pronounced flattening. So, for the euhedral phenocrysts to be flattened and oriented in a certain direction, there must be some kind of compression which caused their alignment and flattening. In the vicinity of Phulad Shear Zone (PSZ), the granites are showing two different sets of phenocrysts: euhedral phenocrysts are showing a trend of NNW-SSE and the deformed phenocrysts with asymmetric tails in their extremities along their length are showing a trend of NE-SW with a sinistral sense of movement which corresponds to the sense of movement of Phulad Shear Zone (PSZ). At the Phulad Shear Zone (PSZ), granites are showing prominent foliation with extremely deformed phenocrysts which are no more euhedral in shape, overall these granitic foliations are showing broad warps and at places they are transformed to a remobilized belt comprising of ultramylonite which is oriented parallel to Phulad Shear Zone (PSZ). So, Erinpura granite is previously deformed as evident from the flattened phenocrysts and was later overprinted by the deformation of Phulad Shear Zone (PSZ) and hence Erinpura granite is older than Phulad Shear Zone (PSZ).

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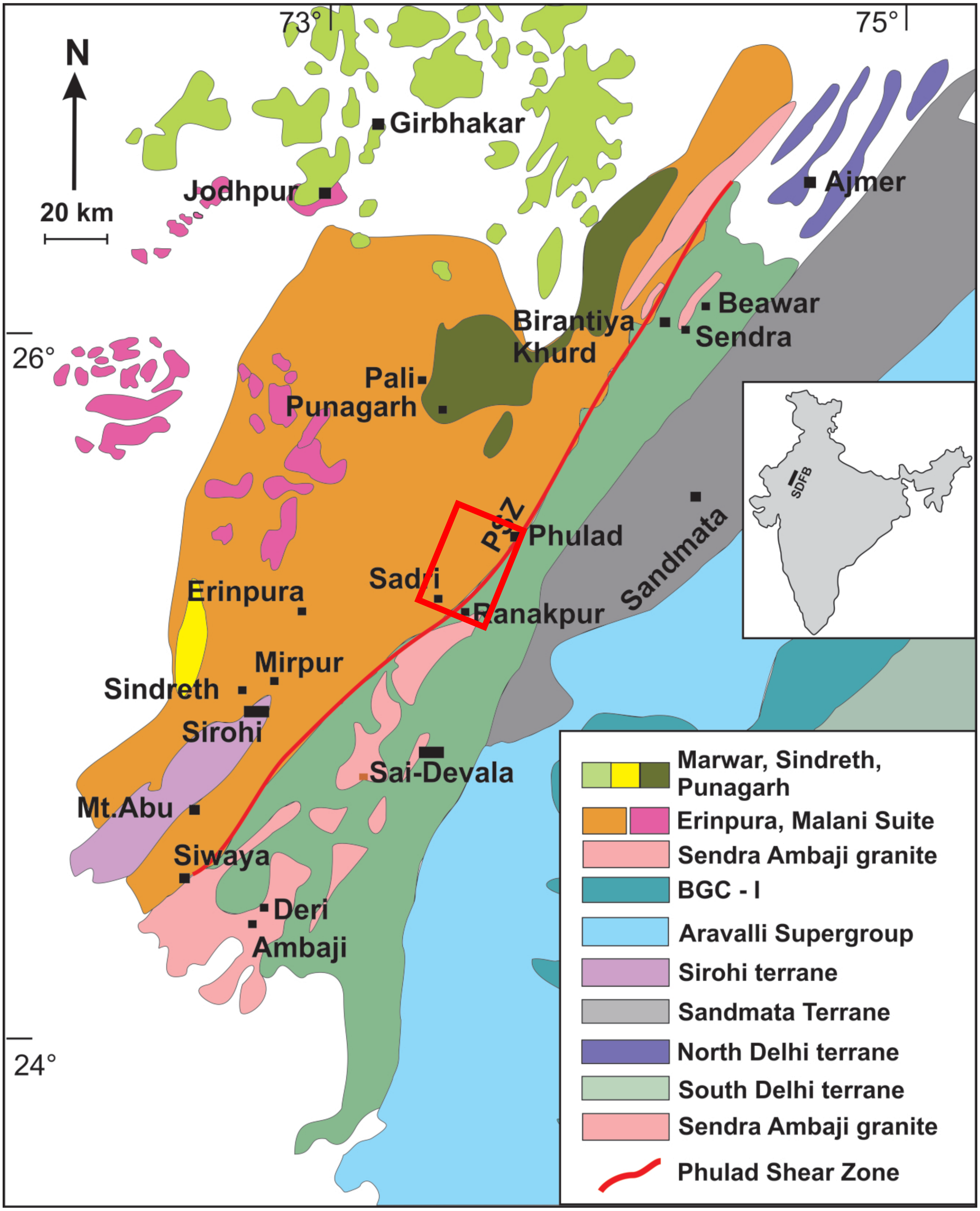

Fig 1.1: Geological map depicting the different crustal domains in the southern part of the Aravalli Delhi Fold Belt (ADFB), modified after Heron (1953), Gupta et al. (1980) and Roy and Jakhar (2002). The present study area is marked by red rectangle.

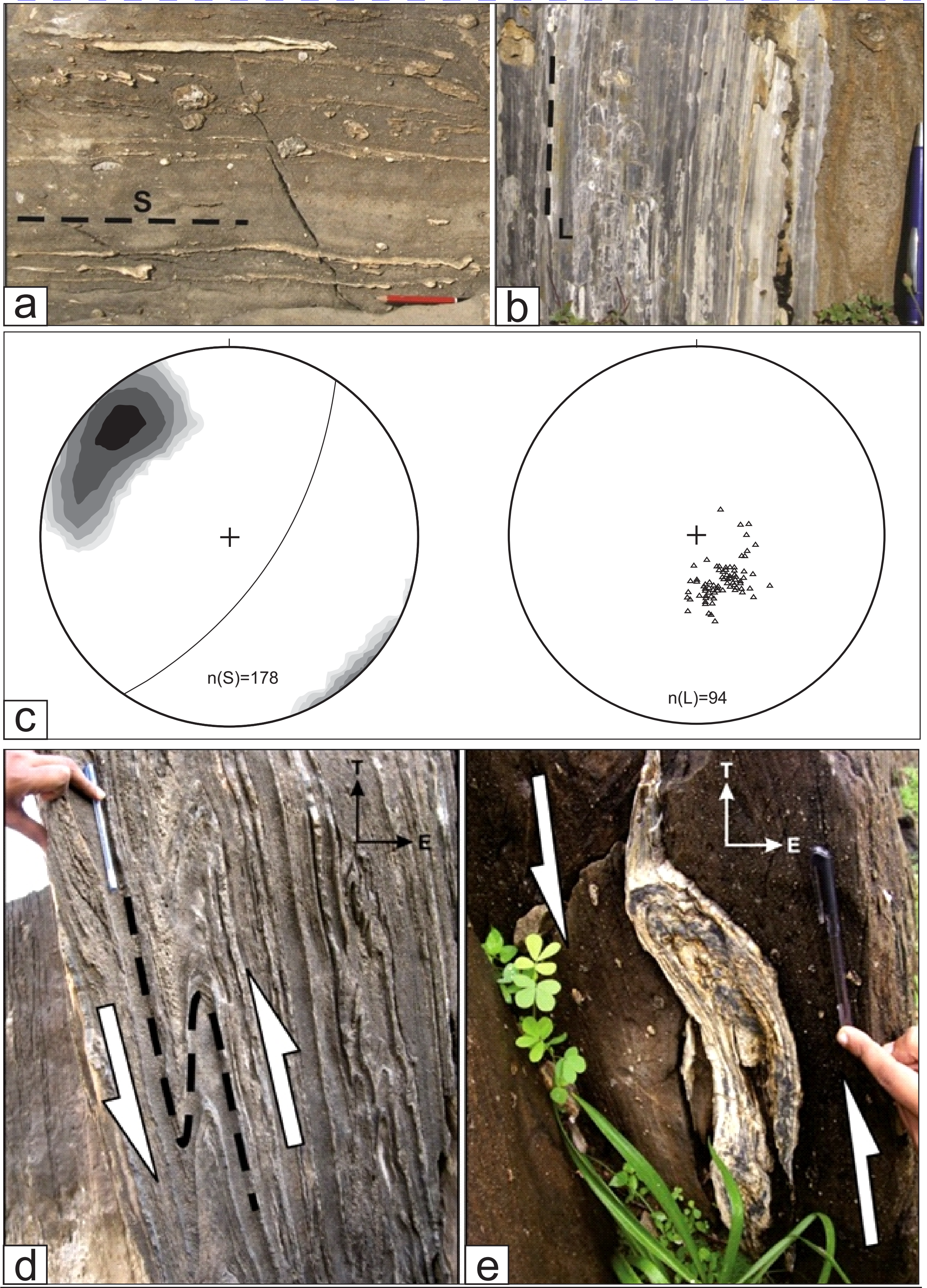

Fig 2.1 Field photographs of PSZ mylonites. (a) mylonite foliation in the intercalated calcareous and quartzofeldspathic metamarl is defined by S, (b) down-dip lineation in the shear zone foliation is defined by L, (c)stereographic projections of Π foliation (contoured) and lineation (filled circles) of the ultramylonite of PSZ giving mean principle orientation $34^0/70^0$E and $60^0 \rightarrow 155^0$ respectively, (d) foliation drag, (e) asymmetric tail of long tectonic clast showing top-to-the-west reverse sense of movement (Chatterjee et al., 2017).

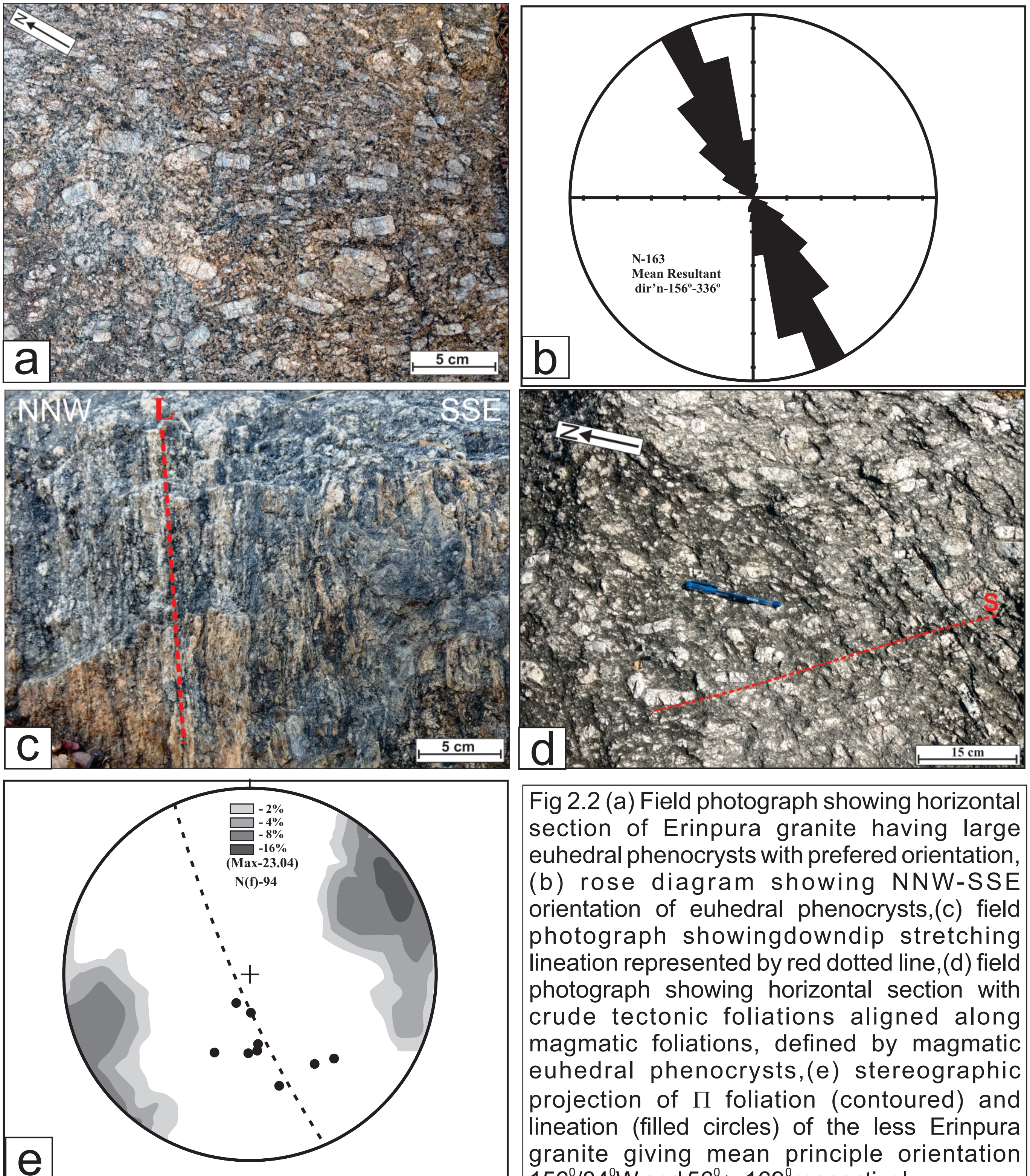

Fig 2.2 (a) Field photograph showing horizontal section of Erinpura granite having large euhedral phenocrysts with prefered orientation, (b) rose diagram showing NNW-SSE orientation of euhedral phenocrysts,(c) field photograph showingdowndip stretching lineation represented by red dotted line,(d) field photograph showing horizontal section with crude tectonic foliations aligned along magmatic foliations, defined by magmatic euhedral phenocrysts,(e) stereographic projection of Π foliation (contoured) and lineation (filled circles) of the less Erinpura granite giving mean principle orientation $156^0/84^0$W and $56^0 \rightarrow 169^0$respectively.

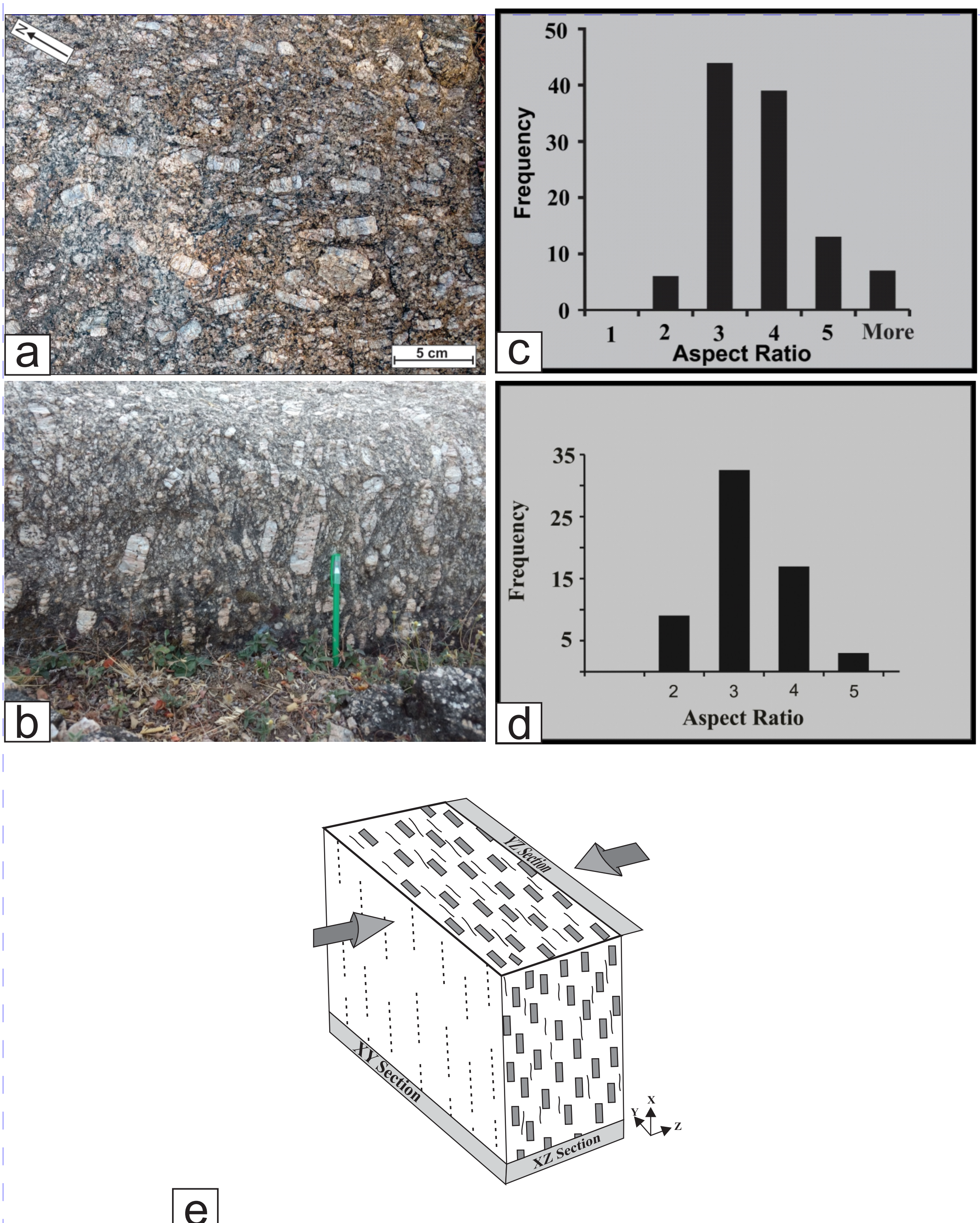

Fig 2.3 Field photograph showing pronounced flattening of euhedral magmatic phenocrysts in (a) horizontal section (YZ section) as well as in (b) vertical section (XZ section),(c) and (d) histograms showing the aspect ratio of feldspar phenocrysts in the Erinpura granite in the horizontal section (YZ) and vertical section (XZ) respectively, (e) schematic diagram showing XY section, YZ section, ZX section where stretching lineations are present in XY section and pronounced flattening of euhedral phenocrysts in

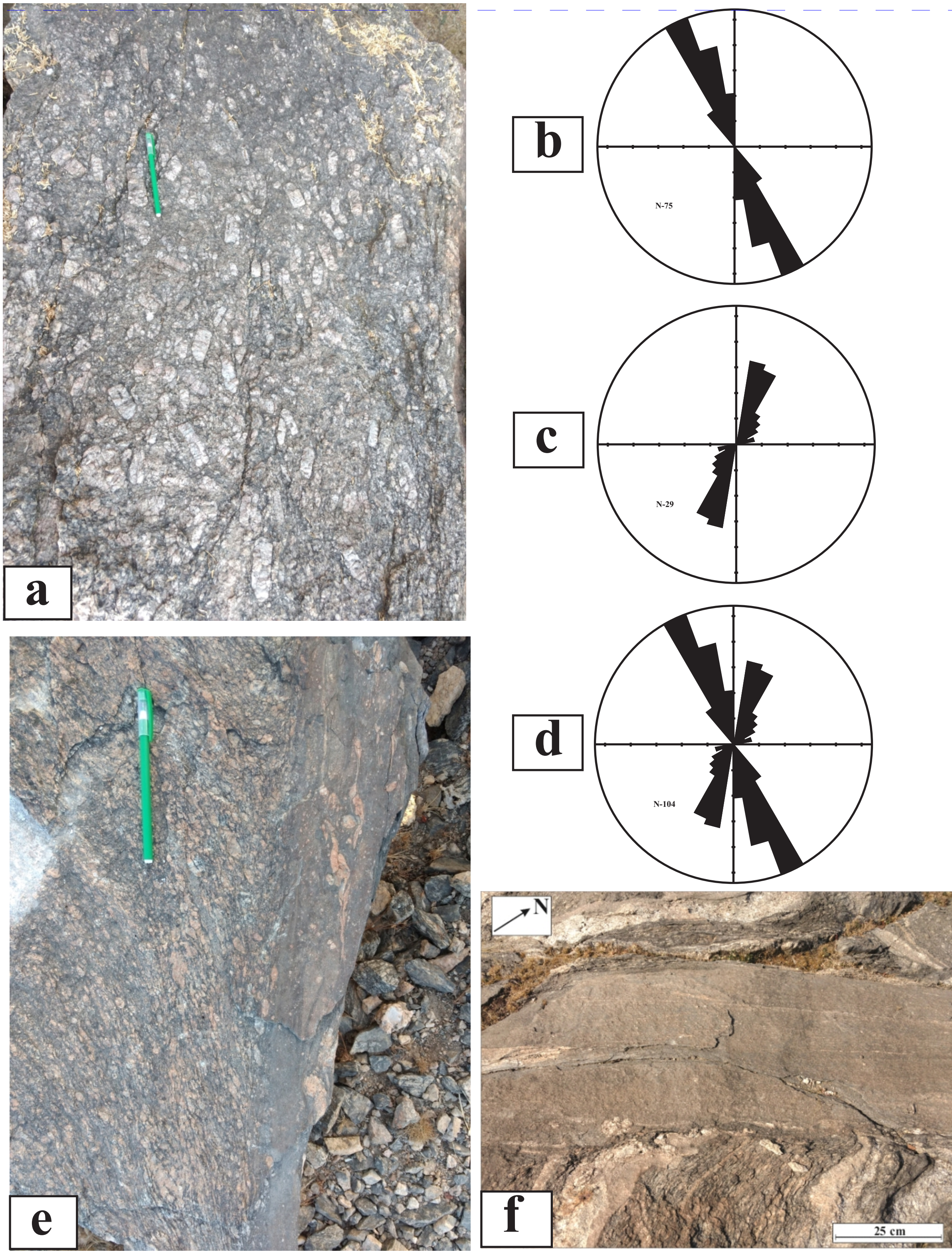

Fig 2.4 (a)Field photograph showing horizontal section of Erinpura granite comprising euhedral and deformed phenocrysts,(b) rose diagram showing euhedral phenocrysts orientation,(c) rose diagram showing deformed phenocrysts orientation,(d) rose diagram showing bimodal distribution of both euhedral and deformed phenocrysts,(e) field photograph showing horizontal section with prominent foliation changing its orientation from NNW-SSE to NE-SW and tranforming into remobilized belt,(f) fine grained grey coloured ultramylonite.

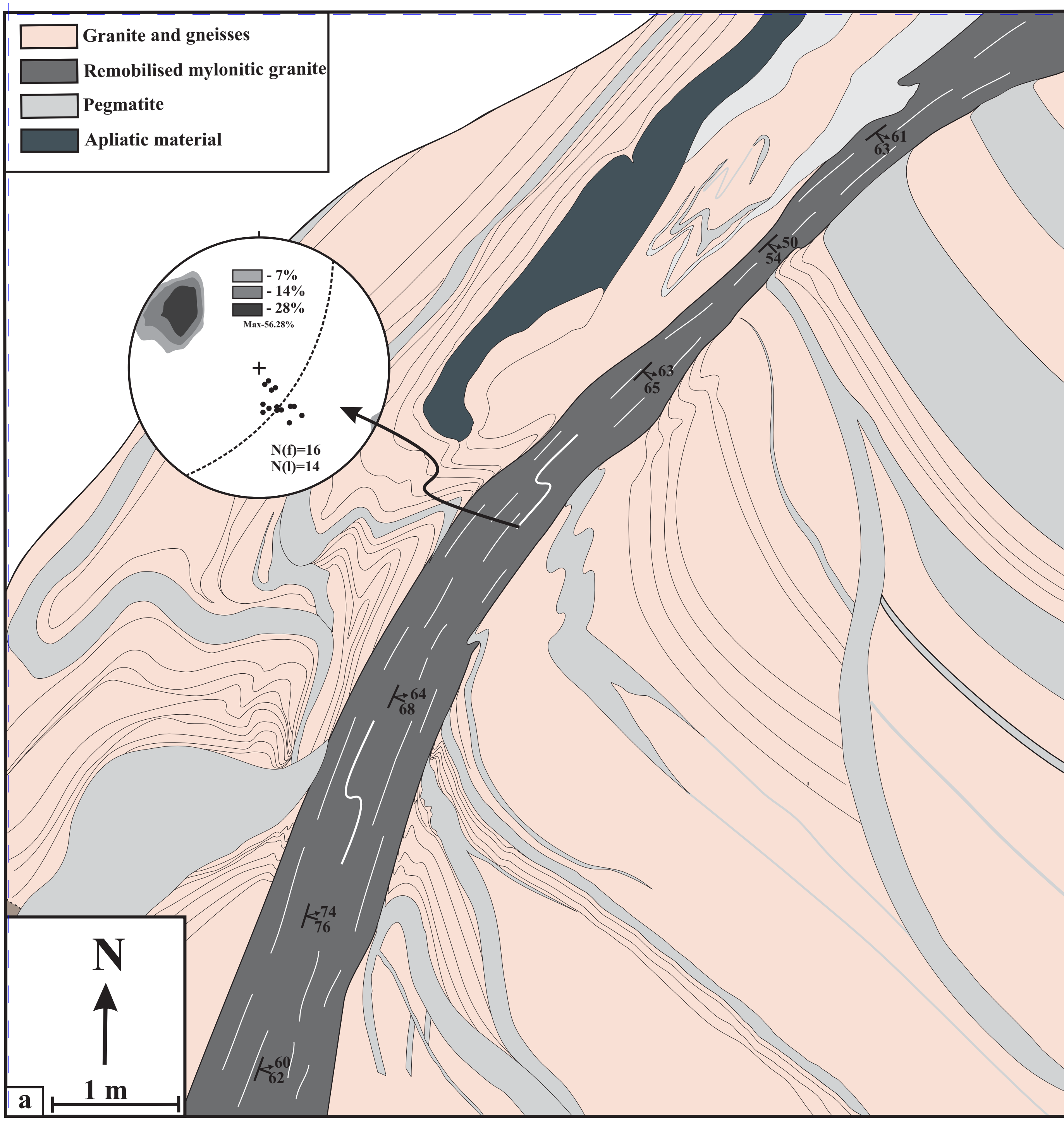

Fig 2.5 Detailed map of Erinpura granite at Phulad Shear Zone (PSZ),stereographic projections of Π foliation (contoured) and lineation (filled circles) of the ultramylonite of PSZ giving mean principle orientation $34^0/66^0$E and $65^0 \longrightarrow 153^0$respectively.

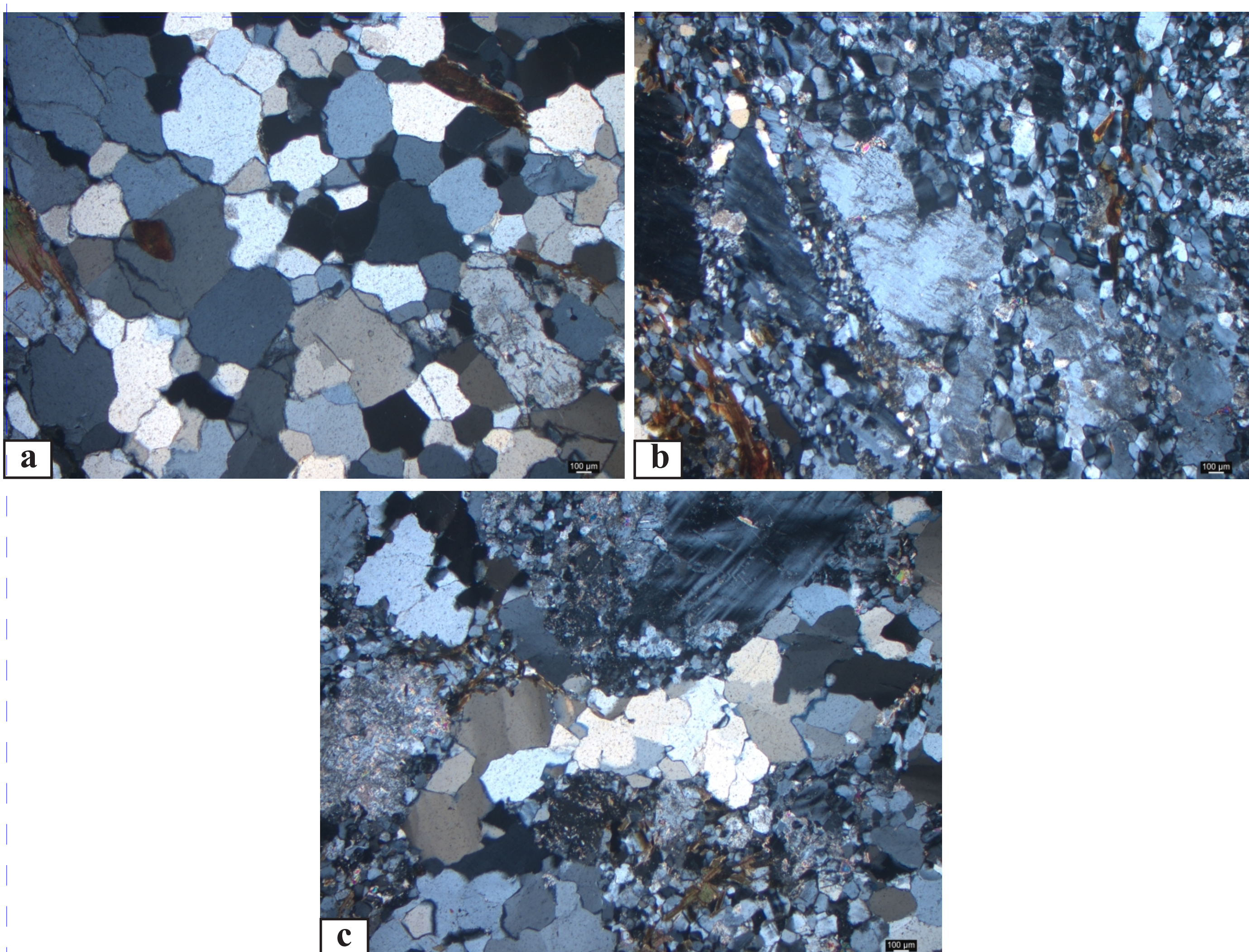

Fig 3.1 (a) Larger recrystallised grains with interfingering boundaries suggests grain boundary migration (GBM), (b)New grain boundaries are forming by progressive rotation of subgrains suggesting a sub-grain rotation (SGR) type of dynamic recrystallization, (c)development of small independent new grains by bulging of grain boundary into the older host grain which suggests bulging (BLG) recrystallization.

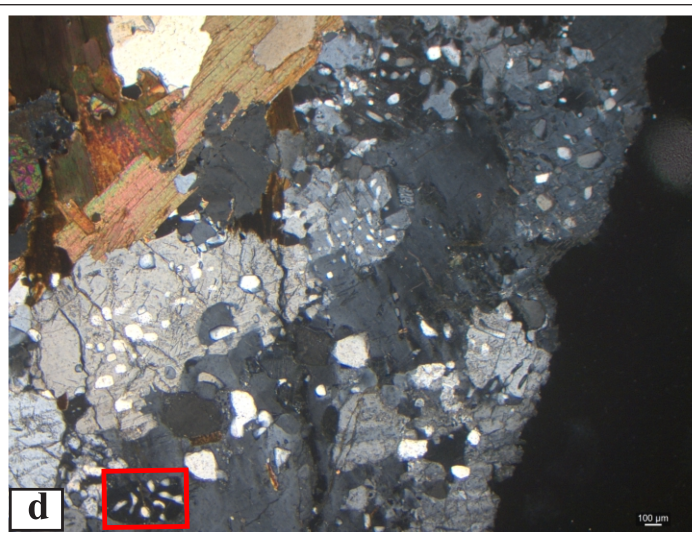

Fig 3.1 (d) Alkali feldspar as blebs in sodic feldspar defining antiperthite,sodic feldspar as lamellae within alkali feldpar defining perthite. Myrmekitic texture is shown by red rectangle.