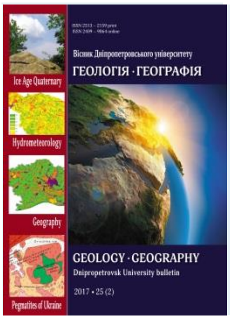

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Strain Analysis in Rock Group of Pur-Basin, India

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Abstract. The work belongs to the scientific direction of tectonophysics, which was called “strain analysis of linear folding structures”. The present study involves analysis of strain in the rocks around Pur, Bhilwara District, Rajasthan (India). The Precambrian rocks exposed around Pur are a part of Pur-Banera belt that is stratigraphically placed within Aravalli Supergroup. The different lithological units exposed in the area are Banded Magnetite Quartzite, Calc Silicate Gneiss, Quartzite and Garnetiferous Mica Schist. These rocks have been subjected to multi-deformational episodes. In accordance with the modern system of multi-level deformation analysis proposed by Fedor Yakovlev in 2012, the results of the deformation analysis at the level of folds (level three of seven) are presented in this work. The outcrop pattern is an isoclinal fold of D2 generation, whose axis plunges steeply NE’ly with an axial plane trending NNE-SSW. The quartzite band in this Pur Synform was sampled for the purpose of strain analysis. This section parallel to the YZ plane of finite strain ellipsoid was prepared (perpendicular to both Schistosity and the lineation). The accepted methods used to estimate strain are a) Fry method and b) “Isogon Rosette” method. The axial ratio of the strain ellipse and the orientation of the long axis of the strain ellipse were computed for every location. It was seen that the strain ratio is nearly uniform in magnitude. The orientation of the long axis of the strain ellipse (Y direction of the finite strain ellipsoid) is also constant in space and parallel to the axial trace of D2 Synform. From the analysis it was suggested a strong flattening following the buckling. The amount of this flattening strain was computed using the”Isogon rosette” method. We calculated reflects the flattening strain recorded in the rock with the very high constancy of the strain ratio and the orientation of the long axis of the strain ellipse irrespective of the methodology adopted. The results of performed researches bring tectonophysics database up-to-date providing an excellent opportunity for provenance analysis of the Pur-basin using the different types of undulose extinction of the quartzite for development of prospective mining projects around the area including iron deposits.

Keywords: strain analysis, Isogon Rosette method, FRY analysis, Pur-Banera Belt, Aravalli craton

Деформаційний аналіз групи порід басейну Пур, Індія

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Резюме.Роботу віднесено до напрямку тектонофізики, який отримав назву «деформаційний аналіз структур лінійної складчастості», головним завданням якого є дешифрування механізму розвитку складчастості, що є ключем до розуміння закономірностей розвитку земної кори і формування багатьох типів родовищ корисних копалин. Представлена робота являє собою результати деформаційного аналізу групи порід басейну Пур району Бхілвара штату Раджастан Індії. Докембрійські породи, що оголюються в районі Пур, є часткою поясу Пур-Банера, який стратигрáфічно приурочений до супергрупи Аравалі. Основними породами, представленими в районі досліджень, є пластинчасті магнетитові кварцити (BMQ), вапняково-силікатні гнейси, слюдисті кристалічні сланці, кварцитові та такі, що містять гранати. Всі ці породи піддані серії мультидеформацій. Відповідно до сучасної системи багаторівневого деформаційного аналізу, запропонованої Федором Яковлєвим у 2012 р., у поданій роботі представлено результати деформаційного аналізу на рівні складки (рівень третій із семи). Детальному дослідженню піддано оголення порід, яке розкриває ізоклінальну складку D_2-генерації, вісь якої круто підвернуто разом з осьовою площиною від півночі – північного сходу до півдня – південного заходу. Для деформаційного аналізу було відібрано групу зразків із сполучної кварцитової стрічки району Пур. Ділянку досліджень обрано паралельною площині YZ кінцевого еліпсоїду деформації (перпендикулярно як сланцюватості, так і системі ліній). Для оцінки деформацій було використано наступні загальноприйняті методи деформаційного аналізу: а) так званий Fry-метод; б) метод “Isogon Rosette” (ізогон-розетковий). Для кожної обраної точки відбору зразків було розраховано осьове відношення еліпсу деформації та орієнтація довгої осі еліпсу деформації. Розрахунки показали наступне: 1) відношення деформації практично рівномірне за абсолютною величиною; 2) орієнтація довгої осі еліпсу деформації (напрям Y еліпсоїду кінцевої деформації) також постійна у просторі та паралельна осьовому сліду D_2 Synform. Висновки деформаційного аналізу: після інтенсивного тектонічного вигину породу було піддано сильному сплющуванню. Величину деформації сплющування було розраховано з використанням методу «Isogon rosette». Розраховані деформації сплющування, що зареєстровані в породі, мають дуже високу постійність відношення деформації та орієнтації довгої осі еліпсу деформації незалежно від прийнятих методологічних підходів. Результати проведених досліджень поповнюють базу тектонофізичних даних, що надає підстави для здійснення глибокого тектонічного аналізу ділянки і басейну Пур з використанням різних типів перетворення кварцитів для розробки перспективних проектів видобутку корисних копалин в межах усього району, включаючи родовища заліза.

Ключові слова: деформаційний аналіз, ”Isogon Rosette” метод, FRY аналіз, пояс Пур-Банера, Аравалі кратон

Introduction. Problem setting. This paper presents the strain analysis results of linear folding structure in Rock Group of Pur-Basin (India). The strain analysis belongs to such a scientific direction as tectonophysics. The first and foremost task of strain analysis is to decipher the mechanism of folding development, which is the key to understanding the development patterns of the earth's crust and the formation of many types of mineral deposits.

The works of the Russian scientist Fedor Yakovlev demonstrate one of the most modern approaches to this direction of geological research. According to F. Yakovlev, the question of the folding mechanism is one of the oldest and most complex problems of geotectonics and structural geology. The unresolved nature of this problem is one of the important causes of the tectonics crisis expressed in the fact that speculative geodynamic models put forward decades ago are used, and new verifiable quantitative models do not appear.

In tectonophysics, the mechanism of formation of folded structures is a description of the geometry of a layered geological environment in conjunction with an external load or with a quantitative description of the shape changes from the initial to the existing one. This problem cannot be solved within the framework of the current dominant paradigm of tectonophysics, since the generally accepted collision folding patterns allow only the most general interpretation of concrete geological structures. From the mid XX century, the interpretation direction was being associated with the creation of speculative models in the interpretation mainly. In the process of establishing the linear folding genesis, two basic questions (deformation magnitude and structure formation mechanisms) could not be completely solved. Thus, lack of strain analysis system has resulted in emergence of a variety of fold structure patterns having low reliability.

At the same time, the folds of the rock layers and the tectonic faults have a great information potential on deformities that can be obtained from field investigations. A correct construction of the geodynamic model of a particular region is possible only when using the tectonophysical approach to the study of geological objects that imply a detailed study of the mechanisms of deformations of folded structures by performing strain analysis. F. Yakovlev proposed a modern system of multilevel strain analysis of linear folding structures (Yakovlev, 2012). This multilevel system allows performing the full diagnostics of fold forming mechanism including reconstruction of pre-fold structure. Proceeding from the above, the expediency of performing a deformation analysis to clarify the geological concept of the specific blocks structure is very high.

The present work is carried out to determine the rate of strain in the selected rock groups of Pur-Banera basin in India.

Objectives of this paper is to clarify the mechanism of crustal folding by means of the strain parameters identification of the Pur site rocks (number and nature of deformation) for evaluation of the lithological and structural regional map proposed by S. Dasgupta in 1982.

To perform work we used two well-established methods, which are the Isogon Rosette method and FRY Analysis (Fry, 1979; Srivastava & Shah, 2008). In accordance with the modern system of multilevel strain analysis proposed by F. Yakovlev, the results of the strain analysis at the level of folds (level three of seven) are presented in this research.

The study area is in and around Pur (25 17.775' N and 74 32.601' E), a village in Bhilwara district of Rajasthan. The study area has a high degree of rock exposure. The urgency of the work is quite high seeing the rocks of the area especially the Banded Magnetite Quartzite (BMQ) have a good economic value and hence mining has commenced recently in the area.

General characteristics of the study area. The study area covers an area of 115 sq. km and forms the southern part of Pur-Banera mineralized belt of Rajasthan. It lies in the extreme south of present map area and is bounded in the North by Kothari River. The area is located in the Survey of India Toposheet No. 45K/11 (Fig. 1). The nearest town, Bhilwara, is 10 km from the study area due north-east. Bhilwara is connected to Jaipur by road and rail services. Bhilwara is on the Ajmer-Chittorgarh state highway and 130 km from Ajmer and 55 km from Chittorgarh. Pur is situated on the state highway connecting Kankroli to Bhiwara and is 12 km from Bhilwara.

The study area has a rolling topography (Fig. 2) with a chain of hills trending NNE-SSW. The topography attains a maximum height of 539 m in the northern part of the study area. The area is dry. Sparse natural vegetation covers the most of the area.

Geological set up of the area. The Precambrian rocks of Rajasthan preserves a record of varied geological and tectonic process beginning from ca. 3500 M.a. The early geological survey of the Central Rajputana commenced in 1908 and continued until 1935. After the survey Heron and his co-worker established the stratigraphy of the region, which mainly comprises of six formations each separated by an erosional unconformity. The summary of the geological formation, as suggested by Heron is given in the Table 1.

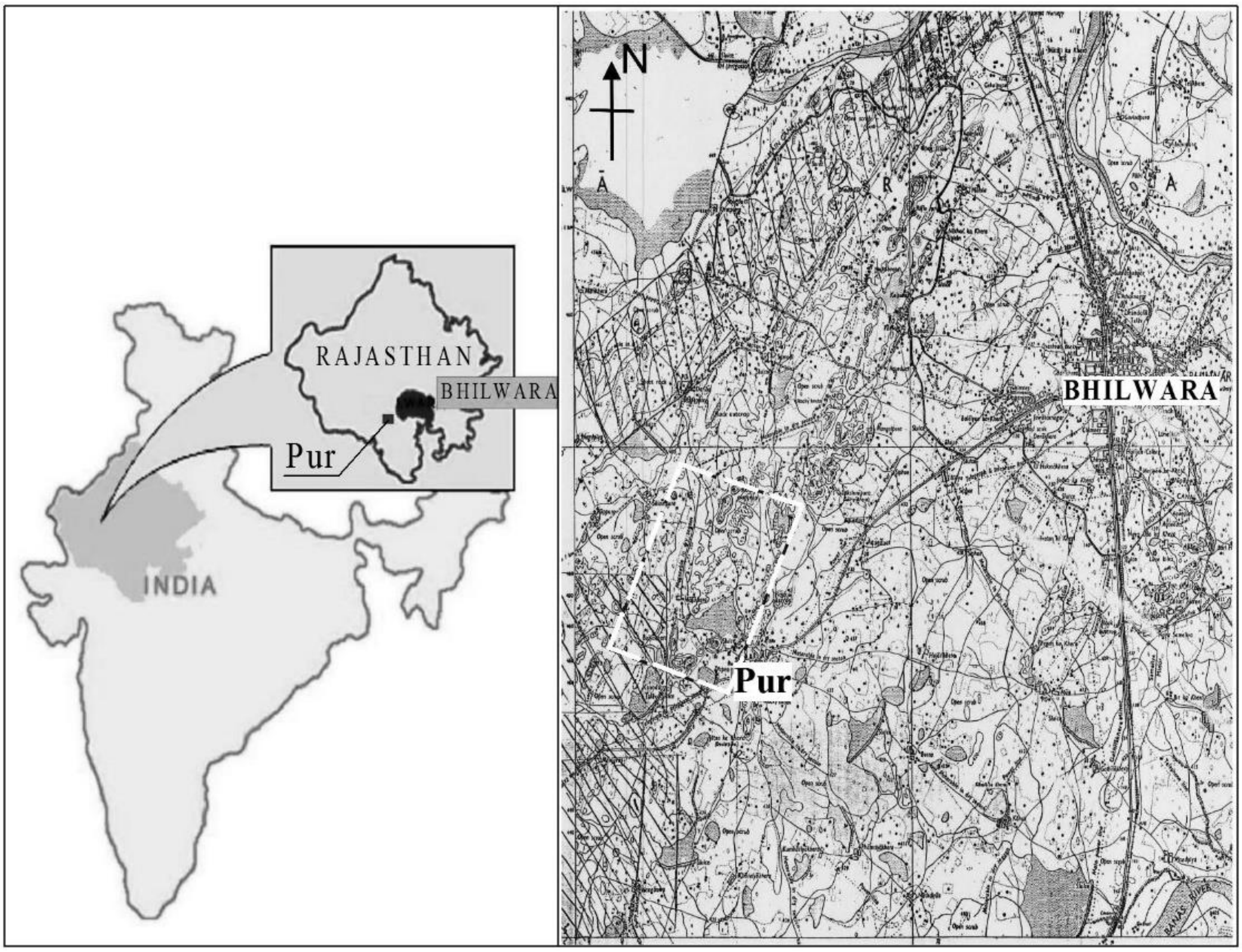

Fig. 1. Toposheet of the study area. Location of the study area in the inset map of Bhilwara district

Fig. 2. Geomorphological mapping of the study area, its physiography and vegetation

Table 1. Stratigraphic sequence of the Pre-Cambrian rocks of Rajasthan as envisaged by Heron (1953)

	Group/Super group	Series	Lithology/Unit	Lithology/Unit (different section)
YOUNGER	Delhi System	Ajabgarh Series	Alluvium and windblown sand ~~~~~~	
			Sandstones, lime stones, dolerites and basalt boulders (age uncertain) ~~~~~~	
			Rhyolites and tuffs ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	Granite, ultrabasic rocks
OLDER			–	Erinpura granite, pegmatite, aplite
			Upper Phyllites Limestones Biotitic limestones and calc gneisses Calc schists Phyllites, biotitic schists and composite gneiss	–
		Alwar Series	Quartzites Arkose Grits and Conglomerates ~~~~~~	
		Raialo Series	Garnetiferous biotite schists Limestone (Marble) Local basal Grit ~~~~~~	
			–	Aplo-granite, epidiorites and Hornblende schists Ultra-basics
	Aravalli System		Impure limestone Quartzite, phyllite, biotite schist Composite gneiss Quartzites grit and local Soda Syenites, conglomerates Local amygdaloids and tuffs ~~~~~~	
	Banded Gneissic Complex		Schists, gneiss and composite gneisses Quartzites	Pegmatites, Granites, Aplites and Basic rocks
~~ Unconformity				

The Aravalli mountain range, which fringes the northwestern margin of the Peninsular Indian Shield, runs for more than 700 km from Delhi in north to Ahmedabad in south. The mountain range is situated between the sandy wasteland of the Thar Desert in west and the Malwa plateau bounded by Great Boundary Fault (Fig. 3) in the east. In plain view, this ancient orogenic belt simulates a distorted hourglass like feature, the thinnest part being to the south of Ajmer.

There are two major Paleo- to Meso-Proterozoic sequences namely the "Aravalli System" and the "Delhi System" (Heron, 1953), now both referred to as Super Group (Sinha Roy, 1984) resting over an Archean basement of Banded gneissic complex (BGC). The Delhi Supergroup rocks known as the Delhi Fold Belt (Gupta & Bose, 2000) is further subdivided into the North Delhi fold Belt (in NE of Rajasthan, developed in three sub-basins in Alwar, Bayana and Khetri areas) and the South Delhi Fold Belt along the main Aravalli hill range in central Rajasthan (Sinha Roy, 1984; Gupta and Bose, 2000) (Fig. 4). There are several intrusions of granitic, mafic, ultramafic and alkaline rocks into the cover as well as the basement rocks. The outcrop of Neo-Proterozoic acid flows, ignimbrites and tuffs (Malani Rhyolites) occur in isolated hills and ridges west of the Aravalli mountain range. The study area lies to the east of the main Aravalli range but the rocks are traditionally thought to belong to the "Aravalli System" (Heron, 1953).

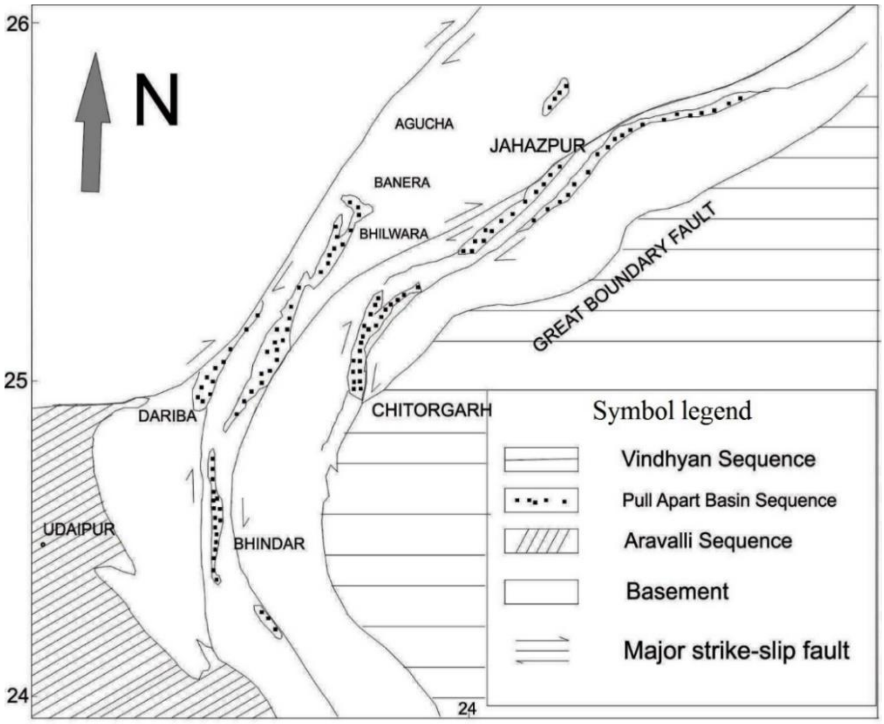

Fig. 3. Disposition of the Aravalli rocks along the eastern margin bounded by the Great Boundary fault, after Sinha Roy (1984)

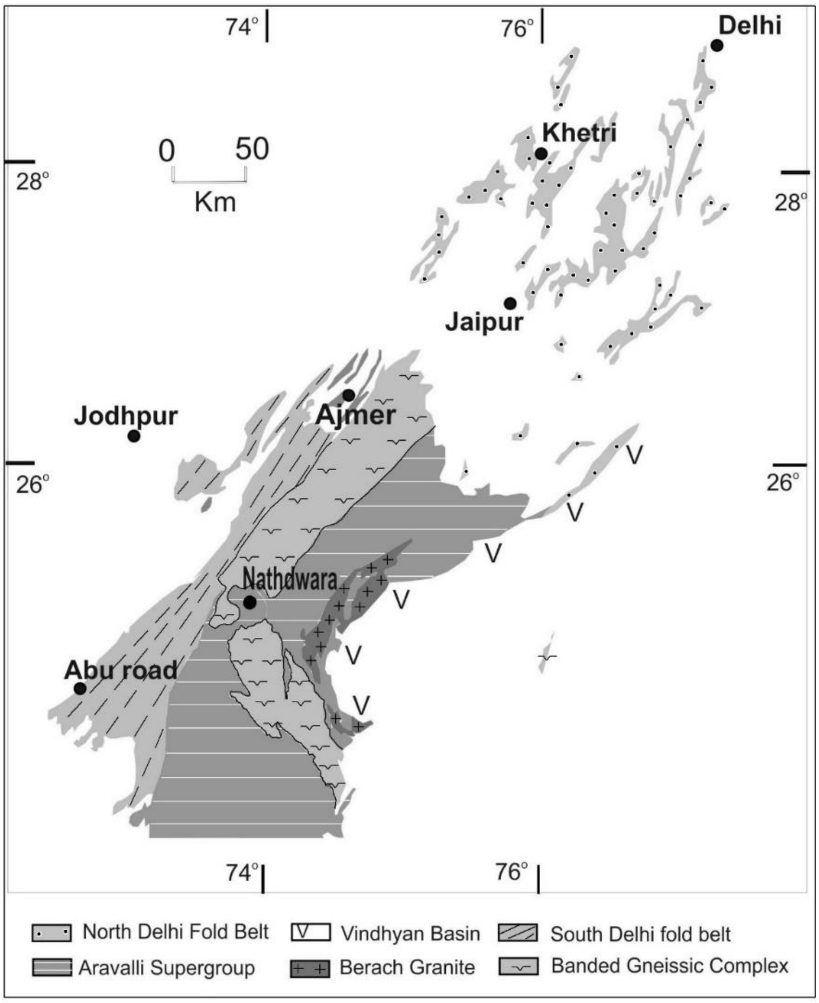

Fig. 4. The regional geological map of the area in Rajasthan (after Heron, 1953)

The rocks of the Aravalli Supergroup known as the Aravalli Fold Belt (AFB) rocks constitute a part of the Aravalli hill range which stretches from north of Gujrat to south Harayana across Rajasthan. The AFB is sandwich between the basement BGC in the east and Delhi Fold Belt (DFB) in the west. The AFB has an inverted V shape with its apex located near Nathdwara area and this belt widens southward. The Aravalli Super Group(type area in Udaipur-Delwara region), making up this belt can be divided into principally two sedimentary sequences, the shelf facies in the east comprising mafic volcanic, coarse clastics and carbonates and carbonate-free deep sea facies in the west containing dominantly pelites with quartzite bands. Sinha Roy (Shina Roy et al, 1993) suggested a bipartite classification for the shelf facies, viz, volcanic-dominated Delwara Group and a volcanic free Debari Group with an erosional unconformity between two.

Apart from the main AFB, sedimentary cover sequences of Proterozoic age occur in isolated and linear belts both in the eastern BGC terrain and in west of the Aravalli hill range. The stratigraphic status of these isolated cover sequences is debated. Afterward Sinha Roy opined that these basins in the eastern BGC terrain evolved as pull apart basins contemporaneous with the main Aravalli Fold Belt (Sinha Roy, 1998). The study area belongs to the Pur-Banera belt.

The complex deformation history of the Aravalli Super Group rocks is now well known. Three main phases of folding (AF_1, AF_2, AF_3) have affected the Aravalli rocks in the main Aravalli Fold Belt. The AF_2 folds are either upright or have steeply inclined axial planes. On profile planes the AF_2 folds vary in geometry from open to tight even isoclinal. The angle between the AF_1 and AF_2 axial trends vary widely from very high being orthogonal to each other, to almost parallel resulting in coaxial geometry. The AF_3 folds which refolded both the AF_1 and AF_2 folds, have sub vertical axial planes with east-west or west-northwest and east-southeast are generally in the form of broad warps and open folds having steep axes. Several faults and ductile shear zones have been recorded in the Aravalli rocks (Roy et al, 1980, 1985). The exact age Aravalli Super Group is not well constrained but the

Berach Granite (2.5 Ga) forming the basement for the Aravalli equivalent rocks in the Chittourgarh area and the 2.5 Ga. Model age of the Delwara matabasalts (Macdougall et al, 1984) suggested its minimum age to be around 2.5 Ga. Isotopic age of 1.8 Ga of the Chawande Granite, Gyangarh enderbite as well as the Pb-Pb age of Galena from Zawar suggested a major thermal event around 1.8 Ga, possibly coeval with the closing of the Aravalli orogeny (Sarkar et al, 1989; Deb et al, 1989). Hence, a time range of 2.5 to 1.8 Ga can be suggested for the AFB.

The Aravalli type rocks are postulated to have developed in ensialic rift-basins in three principal belts, namely the Aravalli belt proper, the Pur-Banera-Daraba-Bhinder belt and the Jahazpur belt (Sinha Roy,1989). The main AFB evolved as an aulacogen widening southward from a triple junction near Nathdwara-Delwara area were rift volcanics are well developed. Two major strike-slips faults of this system emanated from the Nathdwara triple junction one of which opened in Meso-Proterozoic time as the South Delhi rift and the other, emanating from the Aravalli rift near Salumbar and aplaying into multiple strike-slip faults which resulted in the formation of a number of pull-apart basins contained the cover sequence SW in Agucha, Dariba-Rajpura, Pur-Banera and Jahazpur belts. Gupta placed the rocks of Pur-Banera belt with in Railo series, which rest unconformably on the Aravalli schists and Pellites (Gupta, 1934).

Subrota Dasgupta however found no evidence of for the belief of an unconformable contact. He prepared a geological map (Fig. 5) and proposed the structural succession (Table 2) of the rocks from an area covering 115 sq. km, to the west of Bhilwara and north of Pur (Dasgupta, 1969). Inspite of record of multi deformational phases there is no record of any strain measurements in the area. The present work aims to calculate the nature and amount of deformation in the rocks of the area.

Lithology. Following Dasgupta (1969), five different lithological units crop out in the study area. They are Banded magnetite quartzite (BMQ), Calc silicate rocks, Quartzite and. Mica schist.

Of these rocks, the present work was confined to the study of the strain within the qua?-zites band. The 50 m thick quartzite band is folded and shows all the structural details. The map pattern shows that the band of quartzite is folded into a D_3 synform (Dasgupta, 1969) which plunges steeply due NE and has a NNE SSW trending axial plane.

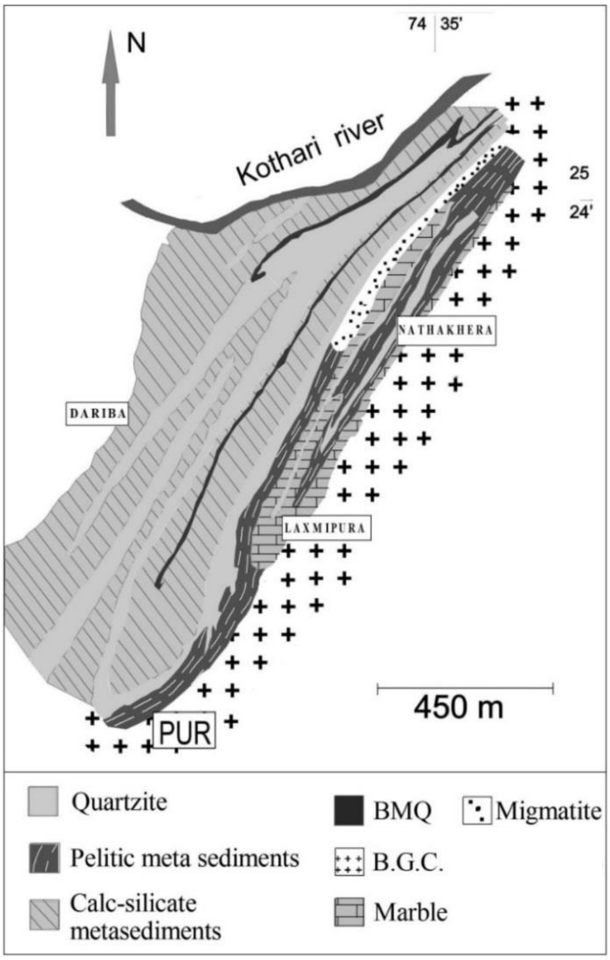

Fig.5. The geological map of the area Pur in Bhilwara District, Rajasthan (after Dasgupta, 1969)

Table 2 Structural Succession in Pur area after Dasgupta, 1969

Direction of younger units	Lithology/Units (Stratigraphic succession of Pur area)
Younger	Intrusive and extrusives including hornblend schists, amphibolites metadolerite, metanorite, pegmatite and quartz veins
	Massive to foliated quartzite (NW of Suras)
	Calc-silicate metasediments (Western part of the area)
	Ferruginous quartzite =? Foliated quartzite (within Pandal Synform)
	Light coloured calc-silicite rock (within Pandal synform)
	Marble (Pandal area and isolated exposure of Jipi area) = ? Calc-silicate metasediments (occurring above quartzite band of Pur closure)
	Massive to banded or bedded quartzite (often interbanded with mica schists)
	Garnetifeous mica schist =? Calc silicate metasediments (just west of Malikhera)
	Banded quartzite (west of Malikhera)
Older	Berach Granite

There are two mappable bands of quartzite. The prominent one, bedded micaceous quartzite (is about 400m thick) occurring structurally below the calc-silicate horizon of Pur Synform (see Fig. 5). It is a coarse grained rock structurally overlying garnetiferous micaschist. Along certain domains, the rock shows alternate layers of schistose micaceous quartzite and garnetiferous micaschist bands indicating primary intercalated nature of the rock (Fig. 6 a, b). These layers are mostly parallel to the bedding plane seen in the quartzite. The thickness of the quartzite bedforms vary from a few centimetres to a few tens of centimetres. The bedding often shows complex fold patterns. The rock is composed of quartz, feldspar, muscovite, biotite and rarely garnet. At places there are clot of kyanite and/or hornblende. The other variety of quartzite contains considerable amount of opaque. It is about 30m thick and is present within the marble at the western limb of Laxmipura Synform.

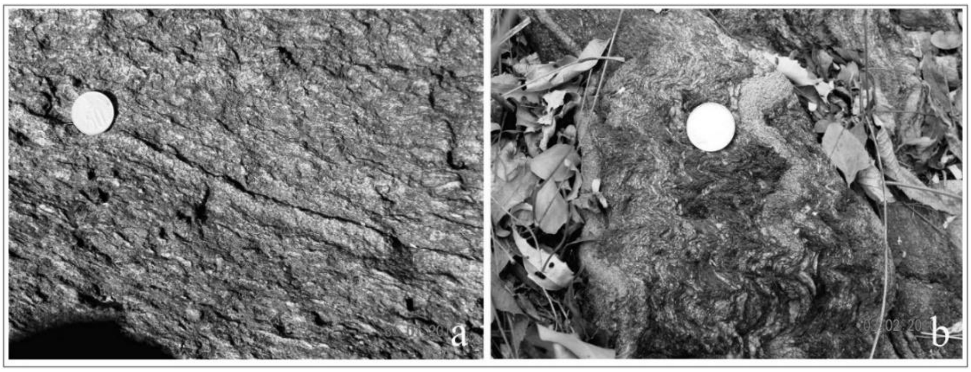

Fig. 6. Alternate layers of schistose micaceous quartzite and garnetiferous mica schist band near Pur

Structural Geology. Dasgupta S. proposed that the metasediments of Pur-Laxmipura area show four successive phases of folding F_1, F_2, F_3 and F_4 (Dasgupta S., 1969, 1982). The earliest F_1 fold occurs in minor scale as rootless, intrafolial, isoclinals structures within quartzites and metapelites. Folds of F_2 generation occur in almost all the rock types of the area mostly in the mesoscopic scale. The metasediments are regionally folded by the F_3 generation into a number of tight antiforms and synforms with NNE-SSW to NE-SW trending axial traces, F_4 structures nearly orthogonal to the regional structures, are gently plunging or warps that have high interlimb angles, usually more than 120^o F_2 and F_3 shows Type 3 type of superposition.

The present fieldwork in the area however suggests that there are three phases of deformation instead of *four* as suggested by Dasgupta (1982). The details of the structural analysis are beyond the scope of this study and hence are not being discussed in details. The rocks of the entire region have been subjected to three phases of deformation namely D_1, D_2 and D_3. The regional synformal folding, which controls the outcrop pattern is a result of the second phase of deformation (D_2) (Fig. 7 a, b, c). The D_1 folds (Fig. 8) are sporadic and found at a few locations mostly restricted to the calc gneiss band. The regional gneissic foliation (Fig. 9 a, b, c) and the schistosity (Fig. 10 a, b) have formed during this phase. D_2 has folded the earlier formed gneissic foliation and the schistosity along with the bedding surface. A spaced foliation has resulted out of the D_2 deformation. The crenulation cleavage (Fig. 11) on the schistosity plane is a product of D_3 deformation.

Fig. 7. Photographs showing the results of the second phase of deformation (the phase D_2):
a – an asymetric minor fold (dextral) within quartzite, folding the bedding surface seen in plane;
b – an asymmetric minor fold (sinistral) within calc silicate gneiss seen in plane;
c – a Hinge of a D_2antiformal folds developed within Mica schist adjacent to the Quartzite near Pur

Fig. 8. Photograph showing Hinge of a D_1 fold in calc silicate rock near Pur

Fig. 9. Photographs showing the regional gneissic foliation formed during the phase D_1:
a – compositional banding within calc silicate gneiss in Pur;
b – compositional banding and variable thickness in calc silicate rock in Pur;
c – gneissic banding within calc silicate rock in Pur

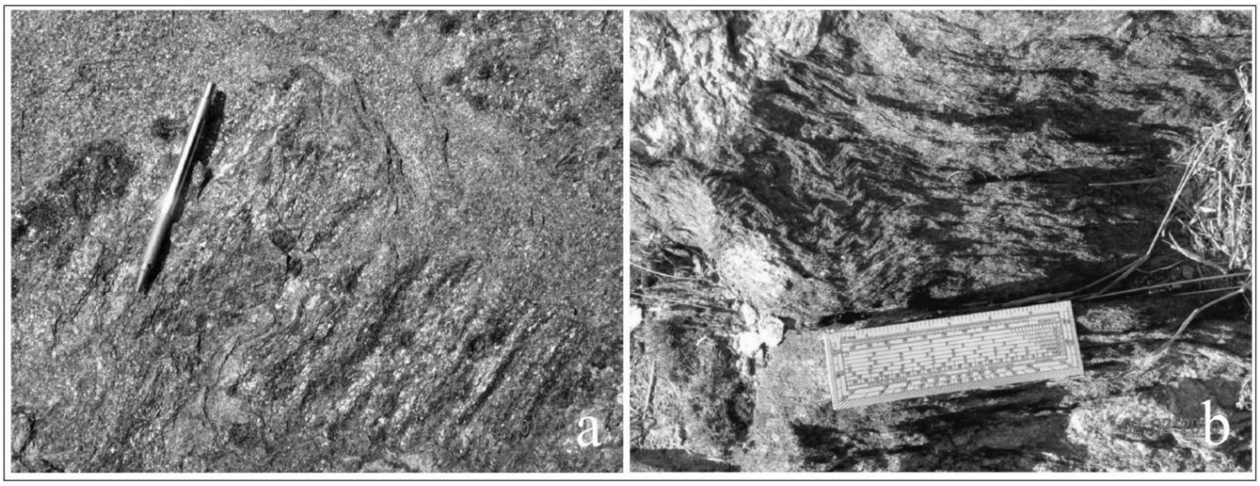

Fig. 10. Photographs showing the schistosity formed during the phase D_1:
a – the regional schistosity in mica schist;
b – the foliation surface developed around the porphyroblast of garnet in the mica schist of Pur

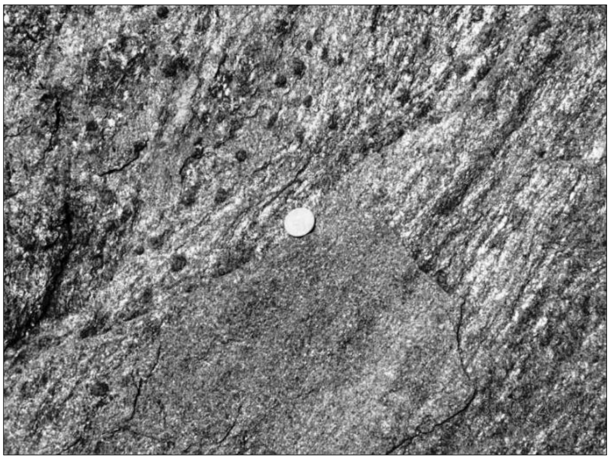

Fig. 11. Photographs showing crenulation cleavage in mica schist formed during the phase D_3

Methods and methodology of strain analysis performing. Strain is the measure of distortion that is fossilized in the rock due to deformation. Strain from deformed rocks can be found out either graphically or algebraically. Strain can be determined on a macroscopic scale as well as in a microscopic scale. Usually marker objects like pebbles, fossils, objects of known shapes are used to determine the finite strain in the rocks. In the present study the strain developed in different domains within the folded quartzite band was probed.

To decipher the amount and nature of strain two different techniques were used. These are FRY method and the "isogon rosette" method. The FRY method (Fry, 1979) was done on the quartz grains of the deformed quartzite and calculates the bulk strain in microscopic scale. The isogon rosette method proposed by D. Srivastava, a rapid method of strain determination, has also been done in the present study (Srivastava, 2008).

FRY analysis. Fry analysis offers a visual approach to quantify characteristic spatial trends for groups of point objects. The technique was originally designed to quantify finite strain based on a 2-D analysis of the nearest neighbors to a central reference point. The FRY method named after the author (Fry, 1969) deals with finding strain in a rock in a microscopic scale. The assumptions of FRY analysis are a) the rock must be monomineralic as far as practicable and b) before deformation the spacing of grains should be statistically isotropic i.e. the distance between any two grains is constant in any direction. It implies that the rock should be composed of minerals of same size and composition to fulfil analyse correctly.

The "isogon rosette" method for rapid estimation of strain in flattened folds. This method acts as a tool for rapid estimation of strain in case of flattened folds and allows the representation of a given fold by a point on the R_s – θ plot, where R_s and θ are the two dimensional strain ratio and the angle between the maximum principal strain and fold axial trace respectively. The method is based the principle which assumes that the isogon deform as a material line during flattening and flattening follows buckling.

The method is mainly based on construction of dip isogons, drawn on profile of a fold by linking the points of equal dip on the inner and outer arcs. These isogons are displaced without changing their orientation until the mid-points of each isogon becomes the common points of intersection of all isogons. The end points of isogons in the rosette trace a characteristic curve that defines the geometry of fold.

Strain Analysis Results. In the present study, FRY analysis have been done on samples of orthoquartzite. Analysis has been done from those domains of the thin sections where the grain size is more or less equal.

Samples for FRY analysis were collected from the different portions of the folded quartzite band. Oriented thin sections were prepared from the samples. Photographs for FRY analysis were taken with the help of the digital camera fitted to the optical microscope (NIKON make) using the NIS element software. The geographic marker lines in the section were transferred to the photographs, thereby orienting the photograph. The software GEOFRY devised by Holcombe was used to determine strain from these oriented photographs. This particular software has two windows. In one window, the oriented photograph is imported and on which the reference line (the geographic marker in the section) is traced. The other window called the plot window shows the trace of the reference line answer plots the grain centres. The plot window has a cross marked at the centre and acts as the sheet of tracing paper that needs to be placed at every grain centre with the plotting of the other centres at a distance from it. As we click on a grain centre in the former window the other centres get immediately plotted on the plot window with respect to the cross at the centre. These results in a void space around the cross and with the help of the mouse an ellipse of suitable geometry can be fitted to this space. The axial ratio of the ellipse fitted is the strain ratio and the angle of the long axis of the ellipse with the reference line gives the orientation of the strain ellipse on that section. The absolute orientation of the strain ellipse is then computed.

To determine the strain in any location more than one section were prepared. This gave different values of the strain ratio and different orientations of the long axis of the strain ellipse with respect to the reference line (Table 3). The harmonic mean of the strain ratios for all the sections of any particular location is taken to be the averaged strain ratio for that location. Similarly, the vector mean of the angles of the long axis of the strain ellipse with the reference line is taken to be the mean orientation of the principal axis of strain.

Table 3. The results of FRY analysis

Sample No.	Photo No.	Orientation of the thin section	No. of points	Axial ratio of the strain ellipse		Orientation of the Long axis of the ellipse		
				Axial ratio on the section	Harmonic mean	With the reference line on section*	Absolute orientation	Mean absolute orientation
L1	L1 2Xa	24/65E	72	2.37	1.81	-15	14 towards 31	24 towards 36
	L1 2Xc		52	1.15		-39	35 towards 43	
	L1 2Xd		50	2.71		-25	22 towards 36	
L7	L7 2Xa	75/50S	47	1.87	1.88	25	24 towards 232	
L9	L9 4Xc	145/60E	80	1.85	1.90	4	4 towards 142	
L10	L10 2Xc	61/65E	83	1.62	1.69	-31	50 towards 206	46 towards 211
	L10 2Xd		56	1.76		-42	42 towards 215	
L11	L11 2Xc	45/85E	91	1.56	1.73	-28	62 towards 214	53 towards 217
	L11 2Xd		100	1.94		-46	44 towards 219	
L18	L18 2Xb	180/55E	100	2.06	2.26	-72	14 towards 9	12 towards 25
	L18 2Xc		61	2.35		-32	44 towards 15	
	L18 2Xd		80	2.42		-68	18 towards 12	

* a negative value indicates anti-clockwise sense of measurement

Starting from Location L1 (in Western Limb) and proceeding towards L18 (in Eastern Limb) following the quartzite band of Pur Synform oriented samples were collected after every 100 m. The description is given below in sequence from Eastern limb to Western limb.

Location 1. Three oriented photographs have been taken (Fig. 12, L1, a, c, e) from the sample collected from location 1. The sample under the optical microscope shows that the rock is made up of quartz and a few feldspar and biotite. There is a strong fabrication which is defined by the parallel and elongated quartz grains. The deformation band and the twin are aligned parallel to this fabric. The corresponding Fry diagrams (Fig. 12, L1, b, d, f) show that the axial ratio of the strain vary from 1.15 to 2.37 with a harmonic mean 1.806. The orientation of the long axis of the strain ellipse with reference line varies from 15^0 to 25^0 in an anticlockwise sense. The absolute orientation of the long axis when plotted on a stereogram (Fig. 12, L1, g) show that the mean orientation of the long axis of the strain ellipse plunges 24^0 towards 36^0.

Location 9. The sample no nine was drawn from the hinge region. Fry analysis was done on a single oriented photograph drawn on the thin section of the samples (Fig. 12, L9, a). The Fry analysis show that the axial ratio of the strain ellipse is 1.05 and the long axis of the strain ellipse is oriented 4^0 clockwise sense (Fig. 12, L9, b). The absolute orientation of the long axis of the strain ellipse plunges 4^0 in a clockwise sense (Fig 3.4 b). The absolute orientation of the long axis of the strain ellipse plunges 4^0 towards 142^0 (Fig. 12, L9, c).

Location 10. The sample shows granoblastic mosaic texture of quartz without any strong fabric of rock. The sample was collected from the hinge. Two oriented photograph were taken from this sample (Fig. 12, L10, a, c). The Fry analysis on these two photographs shows that the axial ratio varies from 1.2 to 1.76 with a mean of 1.68. The long axis of the strain ellipse is oriented at an angle of 31^0 and 42^0 with respect to the reference line in an anticlockwise manner (Fig. 12, L10, b, d). The mean orientation of the long axis of the strain ellipse is 46^0 towards 211^0 (Fig. 12, L10, e).

Location 11. Two oriented photographs were drawn from the sample (Fig. 12, L11, a, c). The rock shows weak fabric defined by alignment of elliptical grain of quartz. There is very little mica and other minerals in the rock. The Fry diagram on these photograph (Fig. 12, L11, b, d) shows that the axial ratio of the strain ellipse varies from 1.56 to 1.94 with a mean of 1.72 (see table 3). The orientation of the long axis of the strain ellipse in the Fry diagram is at an angle of 28^0 and 46^0 in an anticlockwise sense. The mean orientation of the long axis of the strain ellipse is 53^0 towards 217^0 (Fig. 12, L11, e).

Location 18. The oriented photographs were taken from the sample. The rock shows Granoblastic texture without the development of any prominent fabric (Fig. 12, L18, a, c, e). The Fry diagram of this photographs shows that the axial ratio vary from 2.06 to 2.42 (see Table 3). The orientation of the long axis of the strain ellipse varies from 32^0 to 72^0 in an anticlockwise sense with respect to the reference line (Fig. 12, L18, b, d, f). The mean orientation of the long axis of the strain ellipse is 12^0 towards 25^0 (Fig. 12, L18, g).

Plotting of the strain ellipses on the map (Fig. 13) reveal that moving towards the hinge from the limbs there is practically no change (Location 9 being an exception to the observations) in the axial ratio and the orientation of the long axis of the strain ellipses. It is observed that the long axes of the strain ellipse get oriented parallel to axial trace. This pattern therefore indicates that the fold has been formed by buckling and thereafter flattened.

In the present study, the “isogon rosette” method was applied on the folded outcrop pattern of the D_2 synform exposed near Pur. As the fold axis has a steep plunge, the plane of outcrop is the profile plane of the fold on which the analysis is done.

The dip isogons have been drawn and following the method outlined in the Srivastava (2008) the tip of the isogons trace an ellipse, the strain ellipse whose long axis is parallel to the axial trace of the fold and the strain ratio is 2.55 (Fig. 14).

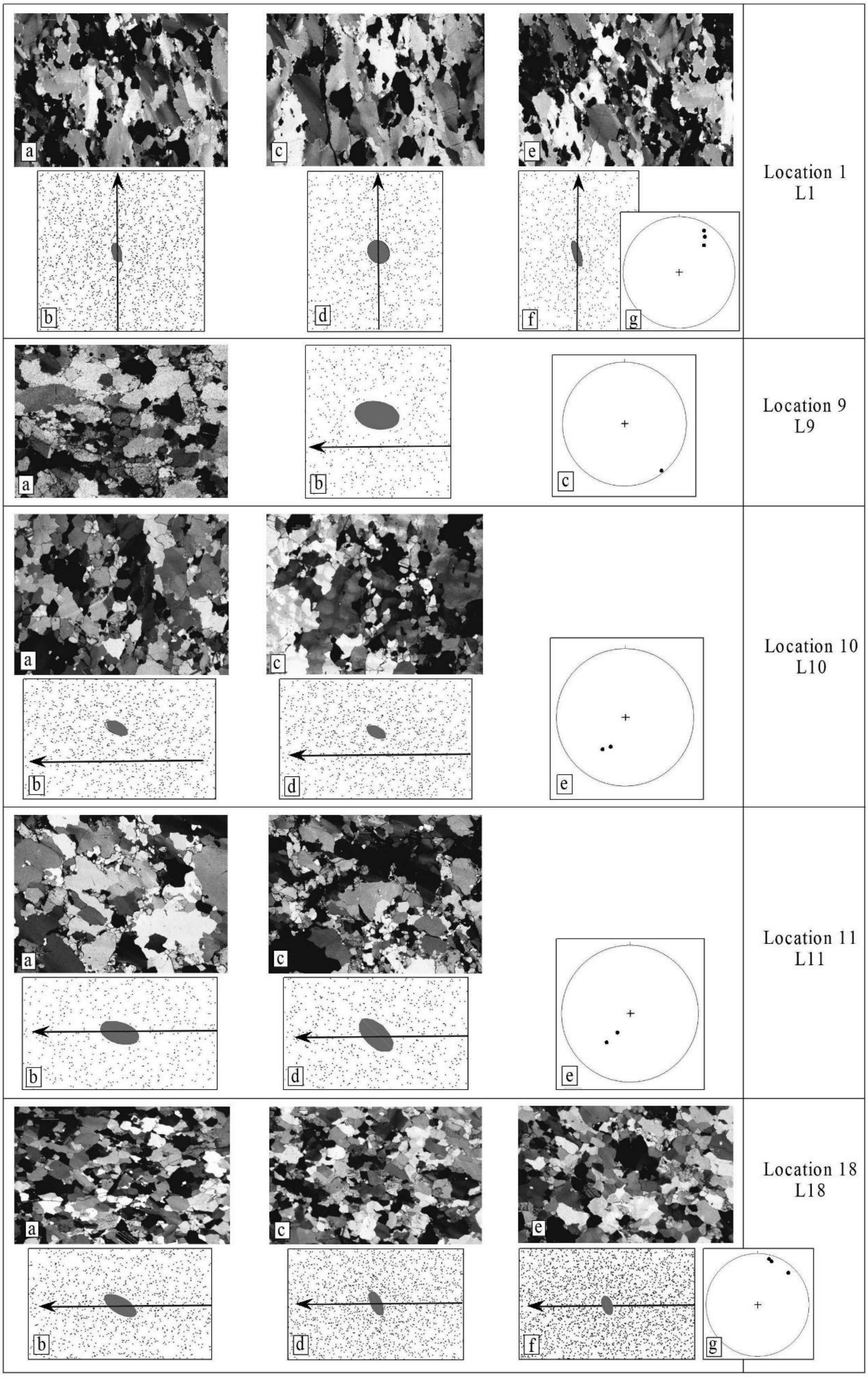

Fig.12. Photomicrographs with the corresponding Fry diagrams for the samples Location 1 – 18 (L1, L9, L10, L11, L18). Equal area projection of the plunge of the long axis of the strain ellipses determined.

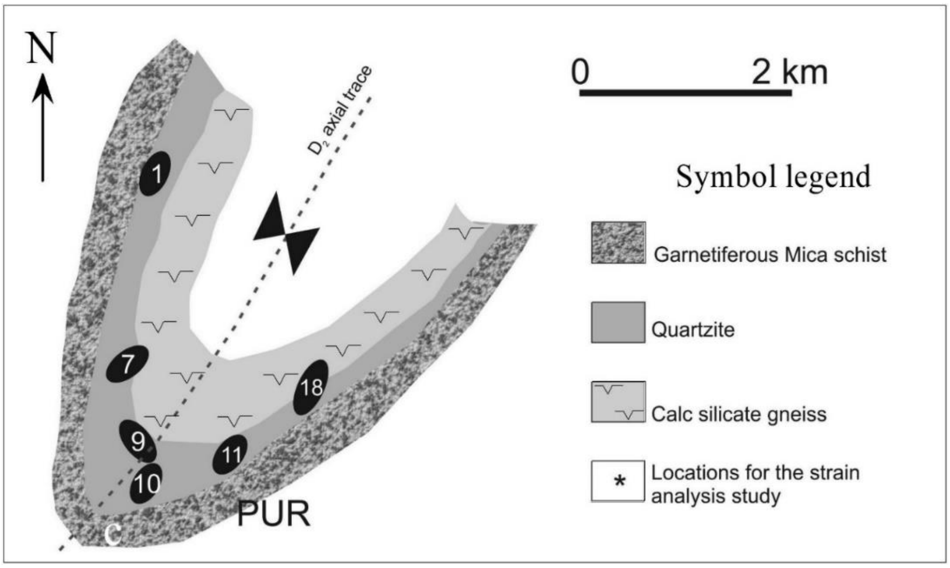

Fig. 13. Geological map of the study area with the location of strain analysis points and orientations of strain ellipses shown on it

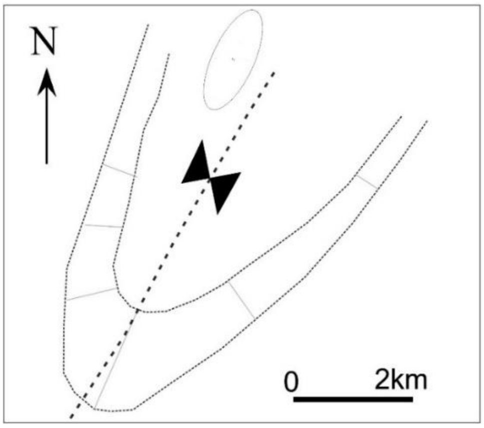

Fig. 14. Strain ellipse drawn by Rosette method of Srivastava (2008)

Conclusions. The study area provides a good opportunity for stain analysis. In the present study, strain analysis has been carried out by two methods: a) using FRY technique; b) using the rosette method.

It is seen after the analyses that the bulk strain is more or less constant in orientation and dimension throughout the area. The near similar geometry of the fold form in the outcrop scale suggests a strong flattening following the buckling, which yielded the fold geometry.

The constancy of the strain ratio and the orientation of the long axis of the strain ellipse irrespective of the methodology adopted are striking. This indicates that the strain we calculated reflects the flattening strain recorded in the rock.

The practical value of this research is the following. The two dominant litho units of the present area of study are quartzite and calc-silicate rocks. The area provides an excellent opportunity to study provenance analysis of the basin using the different types of undulose extinction of the quartzite (Young, 1976). The banded magnetite quartzite (BMQ) is an economic important layering and there has been quick development of prospective mining projects around the area for further exploration of iron.

Furthermore, work results might be of interest for the development of the structural geology theoretical basis and methodological principles for the study of complexly dislocated sites for a forecast of their engineering and geological properties.

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