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Grain Scale physical signatures of early Seismio-tectonic occurrences in fault rock: A study in Gajalia fold belt, Tripura (India)

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ABSTRACT

This paper attempts to assess the microstructural signatures of early seismio-tectonic occurrences which are preserved in fault rocks. For that purpose some samples were collected from a faulted zone of Gajalia, south Tripura. Digital imaging of the thin sections of those samples was performed for assessing grain scale deformation pattern. It has been observed that the tested samples are characterised by moderate foliations and various shapes of grain particles like round, sub-round, angular and sub-angular. The grain scale deformation patterns in the tested samples clearly show that very complex stress pattern at micro level developed during past seismic events. Fluid flows along the margins of foliations are found which is important for weakening mechanism to initiate seismic slip. From the microstructure of the samples it is assessed that various physical processes like stress development, friction and fluid flow play the key role for brittle deformation of grains during seismio-tectonic events. Finally a conceptual model has been developed to explain the physical mechanism of grain scale deformation during early seismo-tectonic occurrence.

INTRODUCTION

Early evidences of seismo-tectonic occurrences are preserved in rocks, as deformations of rocks are commonly subjected to tectonic activities. Most of the catastrophic seismic events or earthquakes are tectonic in origin and related with displacement of rocks or faulting. Lliboutry (2004) defined strong earthquake mechanism as sudden release of elastic energy, which has accumulated in a place over decades, by breaking of the rocks. Earlier Knopf (1931) defined tectonically deformed rock or fault rocks as '*tectonites*'. Sibson (1977), Kirby (1980), White (1982), Wise et al (1989), Chester et al (1985) and Schmid and Handy (1991) attempted to define fault rocks on the basis of cataclasis. White (2001) accorded that development of fault rocks are related with rheology of the host structure and deformation mechanism at different levels. In an early work Cashman et. al (2007) observed complex tectonic processes at micro order. Bell and Etheridge (1973), Wilson and Bell (1979), Mitra (1993), Blenpite et al (1995), Bos et al (2000) and Kato el al (2003) also considered grain size distribution as an important parameter for fault rock analysis. Vernon (2004) presented a general outline on practical approach of igneous, sedimentary and metamorphic rock microstructures and their deformation mechanisms. In a recent investigation Hadizadeh et al (2011) advocated in favour of the efficiency of microstructure study for assessing seismic evidences. Lliboutry (2004) explains that mechanisms of micro scale fractures are related with different types of sliding under stress. Local rheology is considered as an important static factor under high strain condition, as lithostatic pressure (stress resistance of rocks) is related with it. All the previous studies established that micro scale seismo-tectonic deformation (elastic behaviour of rocks) takes place by the combined functions of some physical processes namely:

a) Stress (tension or compression) (S) creates primary fracture
b) Friction (F) due to slip along the fracture line
c) Fluid flow (H) provides weakening mechanism to initiate seismic slip.

Considering the significant importance of deformed rock or tectonite microstructure analysis, we have decided to perform a study on the grain scale evidences of physical processes in a seismo-tectonic zone. The main objective of this study is to assess the influence of complex seismo-tectonic occurrences on deformed rock microstructure characters.

STUDY AREA

In the present study a faulted zone of Gajalia fold in South Tripura district has been selected (Fig.1). This area lies between the latitudes 23°02′35″N to 23°09′27″N & 91°26′47″E to 91°32′04″E. and bounded by Indo–Bangladesh border in the north, south and west and Baromura hill range in the east. Gajalia fold area is located in a part of northeast India, which is known as one of the most seismically active regions of the world (Gupta and Singh, 1982; Guha, and Bhattacharya, 1984; Agarwal, 1986; Kayal, 1987; Gupta, and Singh, 1986; Gupta, and Singh, 1989; Gupta, 1993; Kayal, 1998;). According to Bureau of Indian Standards (BIS) seismic hazard map of India updated in 2002, this area under Zone V. The geological succession of this area shows that during the Miocene the area under review was dominated by marine-coastal environment (Dey, 2005). Stratigraphically this fold belt is characterised by uni-models (sand and clay alteration) and some cross beddings. Some prominent east-west and north-south morphotectctonic lineaments are also observed in this area. In a very recent work Dey et al (2011a) identified some seismic slip evidences in the study area, Gajalia fold belt.

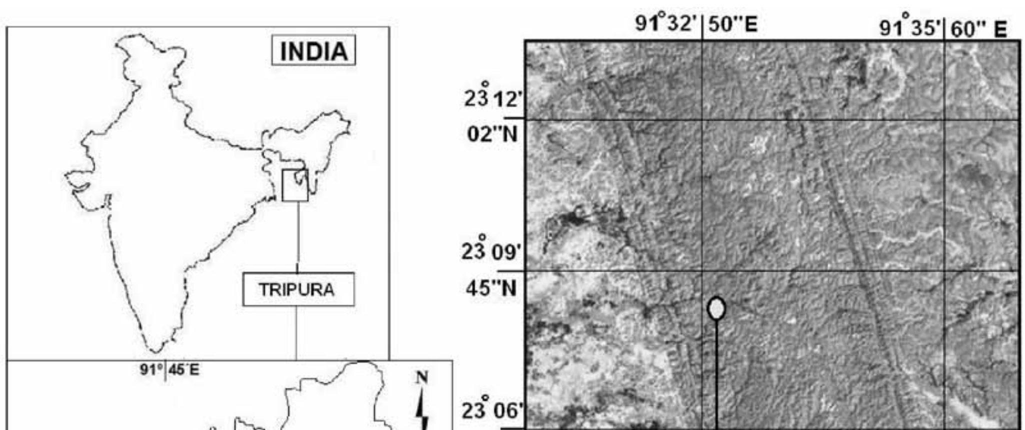

Figure 1. Location and environs of the study area (photograph shows the faulted zone)

METHODOLOGY

Sampling and thin section making:

As this study aims to assess the microstructural evidences of deformation, rock samples from different layers were collected from a faulted zone near a streamlet known as Gajalia Chara. During the fieldwork rock samples were collected for laboratory testing. Some common equipments like steel knife, sample plate, petrography glass slides etc were used for preparing thin sections in the laboratory. Core cutting and grinding machine was used for initial cutting of the hand samples. Resin and hardener (araldite) were used in 1:1 ratio for fixing the samples on glass slides. An ordinary sharp edged small stainless steel blade was used in removing the araldite coating from the outer parts of the fixed sample. Polishing and lapping machine was used for making the thin section . Actually one perfect flat surface of each 30μm thick sections were needed for this study through which light can be transmitted easily. An electric warmer was used for drying the samples in very mild temperature (30^{o}C).

Imaging and analysis:

Imaging and analysis of the thin sections is standing on (i) microscopy and digital imaging and (ii) image analysis. Studies carried out by Protz and Sweeney (1992), Hibbard (1995), Mees et al. (2003), Pugliese and Petford (2001) and Monga (2007) were consulted in computer-aided construction of three-dimensional images, for the analysis of grain particles . Optical microscope (inverted) and a fixed high resolution digital camera were used for thin section imaging. Sophisticated image analysis software was used for assessing micro scale signatures. Digital sketches of the samples were prepared under high level brightness and contrast for identifying the flow veins. Prominent parts were selected and finally presented by inverted colour (flow veins are shown in black). Different parts of the images were selected and brightness-contrast slicing (BCS) method was adopted for assessing the grain scale deformations. Recently Dey et al (2011a) successfully used brightness-contrast slicing method for assessing quartz grain arrangements. In another work Dey et al (2011b) improved that method by advanced soft computing. In this method high transmittable particles became very prominent in the digital images by increasing the brightness-contrast ranges and optical analysis of deformation patterns. High level accuracy can be achieved through this technique.

RESULTS

Microstructure and grain scale geometry:

The thin sections show that the selected samples are moderately foliated (Fig.2). Among the tested samples 1 and 2 are the good examples of wide range of variations in grain sizes. Sample 3 is characterised by comparatively larger particles. Apart from the size of the particles, wide ranges of grain shapes are observed in the tested samples. In sample 1 round to sub-round grains are found along the flow veins. Dilation by hydrothermal alteration might influence the modification of larger grains (particularly Quartz) into round shapes. Sample 2 is characterised by sub-round and sub-angular patterns. Some sub-round shaped larger quartz particles are found near the flow path. Angular to sub-angular patterns are found in this sample (fault breccias). Gouge veins were also developed within the fault breccias. In sample 3 most of the particles are shaped round or sub-round in this sample. Some small sub-angular particles are also observed in this sample, though these are very few in number.

Evidences of stress development and grain boundary sliding:

The grain arrangement patterns in the samples clearly indicate that both normal and shear stress developed at grain scale in the rocks of the study area (Fig.3). As the crystalline particles (hard quartz) have greater stress resistance than the other minerals in the selected samples, it has been observed that prominent shear stress developed on quartz grains. Sometimes, high level friction by parallel slip decreased the stress resistively. Normal stress might influence on those grains to create breccias (for example Fig. 3: sample.1: a, c; sample.2: a, sample. 3, b). Away from the flow veins some sub-angular grains are found in sample-1. Shapes of those grains might be modified by very high velocity friction during grain boundary sliding.

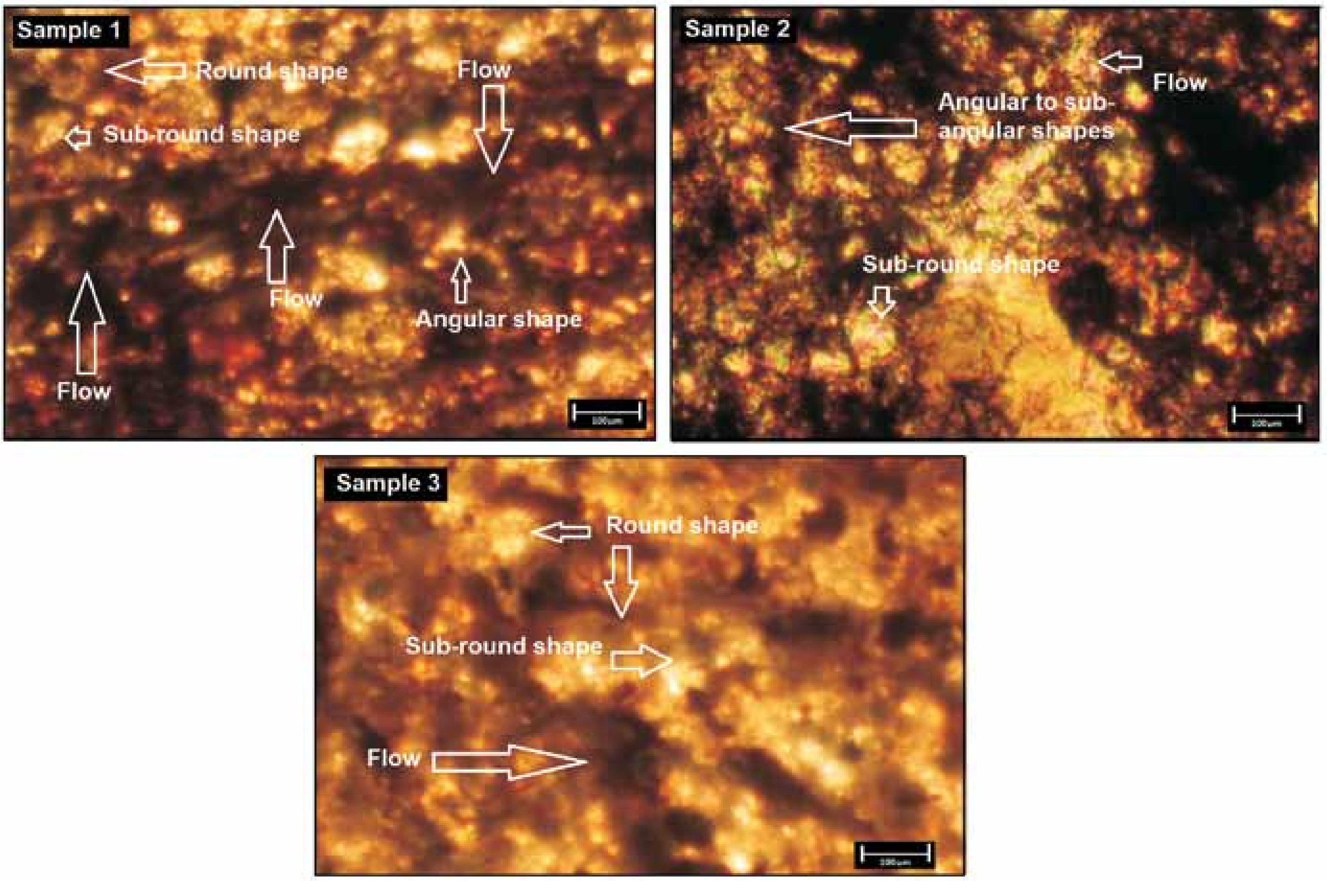

Figure 2. Micro-photography of the selected samples show the general microstructural physical characters (prepared by inverted microscope)

Fluid flow:

All the tested samples show that the high level fluid flow took place by thermal / hydrothermal alteration. The evidences of grain patterns along the flow vein strongly support that fluid pressure must be equal or higher than the lithostatic pressure to accelerate dilatation (Fig.4). In sample-1 fluid flow observed along the margins of foliations might cause re-crystallisation by thermal/hydrothermal alteration affect. Sample-2 shows a very strong fluid flow through the fracture line, which resulted in prominent seismic slip at micro scale. Huge temperature and pressure might play important role for the movement of flow crossing the normal foliation range. Crystalline process also occurred during the heating and cooling of the melted materials. Sample- 3 indicates that fluid veins developed at micro level flow towards different directions by huge pressure of flow. It is a typical example of fluid flow networking through the gouge veins.

CONCEPTUAL MODELLING ON PHYSICAL MECHANISM OF GRAIN SCALE DEFORMATION AND SEISMIC FAILURE

Based on the above observations we have attempted to develop a simple conceptual model for explaining the physical mechanism of grain scale brittle deformation during early seismo-tectonic events. Evidences of the tested samples prove that grain scale deformation (elastic behaviour) took place by complex stress development (normal and shear), which resulted in multidirectional grain boundary sliding in the study area. The variation of stress pattern also indicates the role of controlling factors like gravity and lithostatic pressure in deformation mechanism. It is well accepted that gravity plays very important role to accelerate the slip / displacement from micro level to regional level. From physical point of view, if it is considered that gravity (g) is fixed (constant) during the period of tectonic movement (t) the other three processes like, stress,

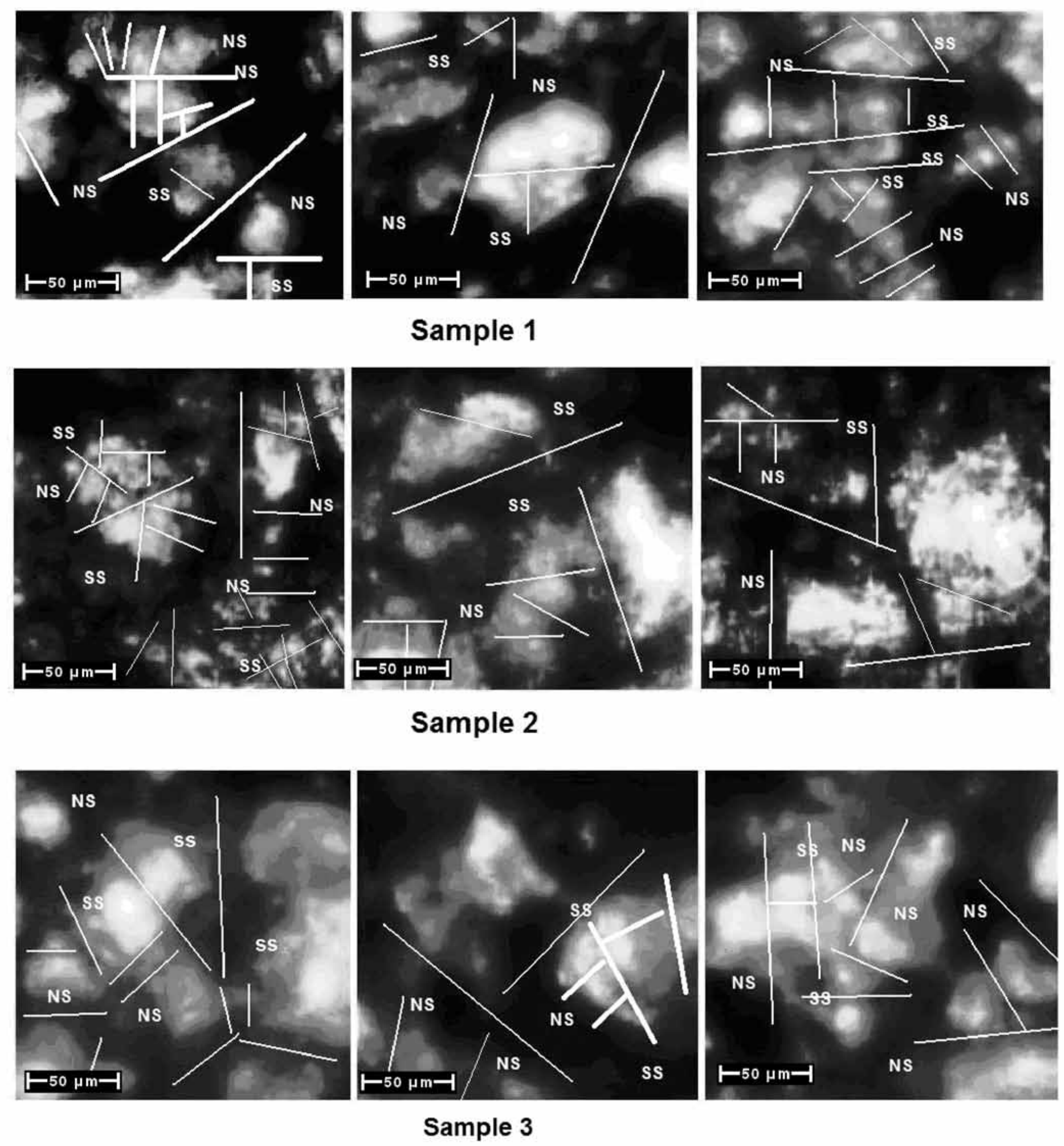

Figure 3. Grain scale deformations in different parts of the selected samples (straight lines shows estimated grain boundary friction; NS=normal stress, SS=shear stress)

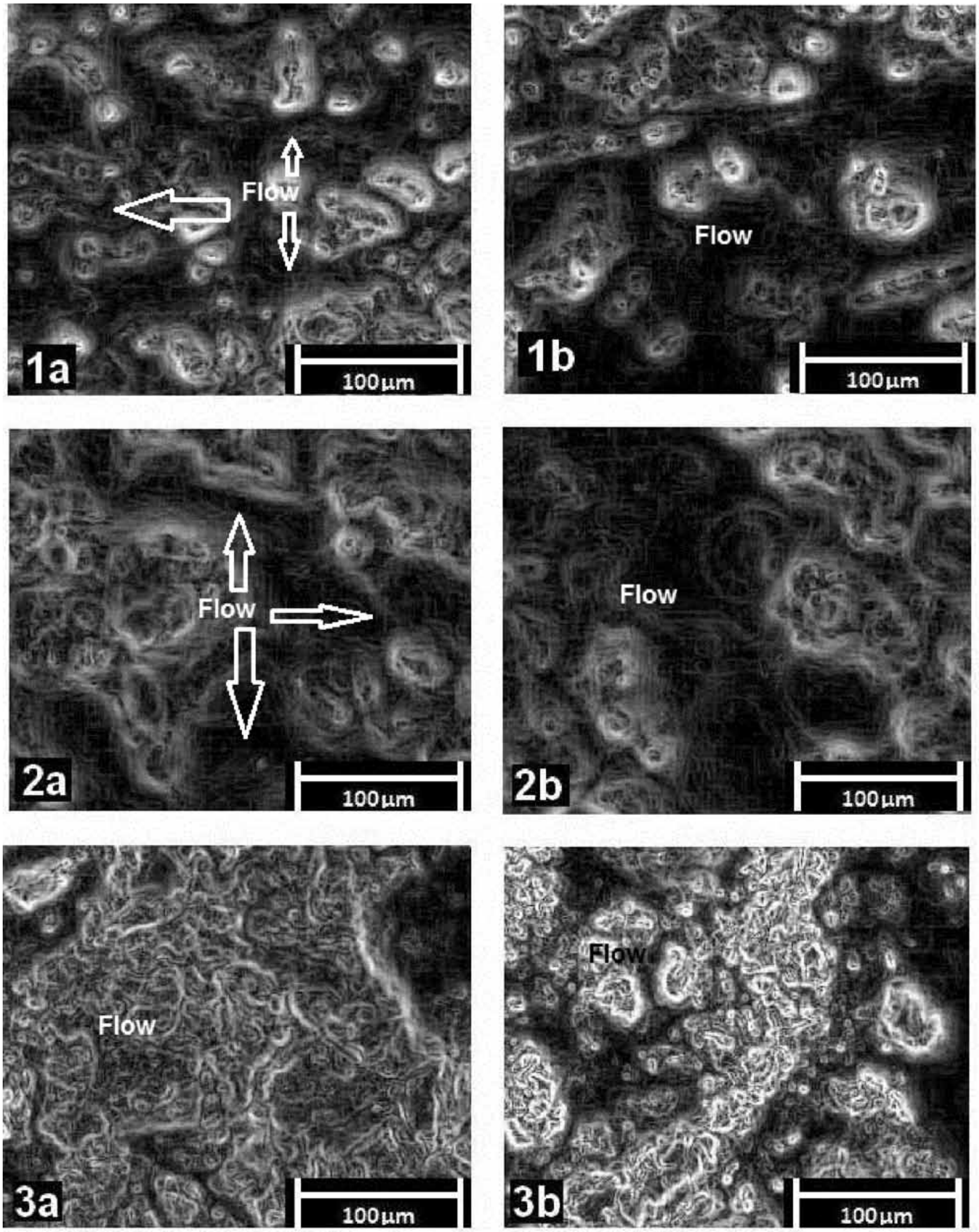

Figure 4. : Fluid flow in some parts of the tested samples 1, 2 and 3

friction and fluid flow must be variable with time for resulting deformation and displacement. We have attempted to explain the deformation process by seismic failure by a very simple conceptual model, which is as follows:

$$N = [f\,(S_\alpha,\ F_\beta,\ H_\gamma)^{\,t} / \Delta]g \qquad \text{.........} (1)$$

Where,
N= Deformation by seismic slip / displacement
f= Functions of the physical processes
g= Gravity (constant within t)
α= Direction and level of stress (variable with associated factors within t)
β= Level of friction (variable with t)
γ= Amount and velocity of fluid (variable with thermal / hydrothermal alteration within t)
Δ= Local rehology

Though the variations of friction and fluid flow during deformation cannot be explained by optical micrography, the geometry of deformed particles preserve the evidences of stress patterns at grain scale. From the observations of the tested samples it is also proved that lithostatic pressure of the grain particles play important role in the development of stress pattern and resulted energy diffusion. It has been observed that finer particles are commonly marked by brittle deformation due to normal stress development. However, prominent influence of shear stress has been observed by medium size grains (particularly hard quartz grains). In the medium grains initial fractures might be developed by compression and later shear stress developed, which accelerated parallel slips. In that case if the lithostatic pressure (stress resistance of the grains) remains not less than the increasing stress (normal) within considerable time, alternative shear stress may develop to defuse the extra stress energy (Fig.5a). Here stress energy defusing process and shear stress development can be explained by:

$$D = P \geq (S_\alpha)^t \qquad \text{............} (2)$$

Where,
D= Defused stress energy
P= Lithostatic pressure (constant within t)
S= Increasing stress (normal) within t

On the basis of the above concept it can be said that brittle deformation by normal stress can be developed under the opposite condition (normal stress > lithostatic pressure) (Fig.5b). Very prominent marks of fluid flow in the examined fault rock microstructures strongly support that the process of seismic slip started under a changing temperature condition during high velocity friction. Thermal or hydrothermal alterations resulted fluid flow and grain boundary sliding in a large area. That process played a vital role in weakening the structural arrangements and finally local gravity enhanced seismic failure from micro scale to large area.

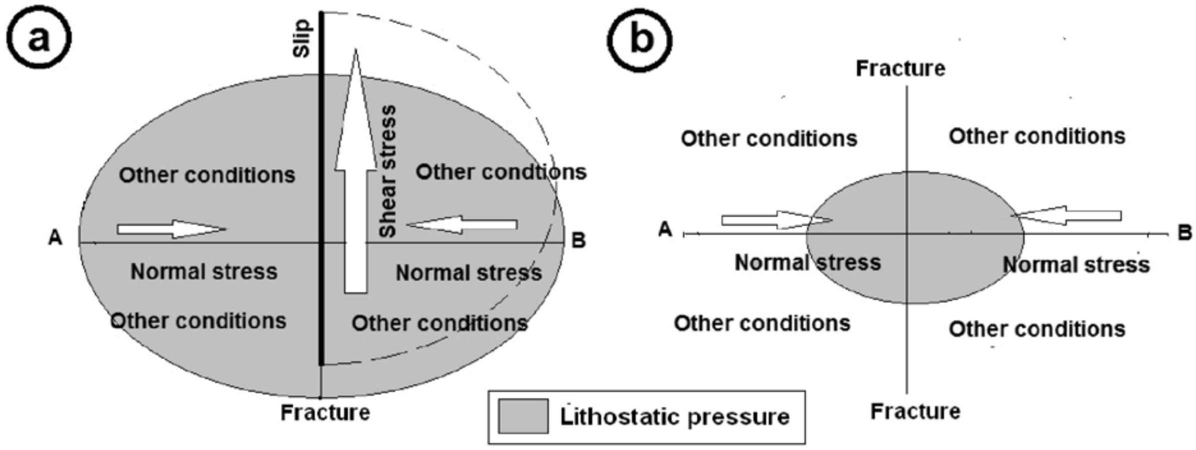

Figure 5. Theoretical frame up of deformation types at grain scale (a) development of shear stress where lithostatic pressure is not less than normal stress as expressed in equation-2 (b) deformation by normal stress where compression is greater than lithostatic pressure (AB indicates normal stress level ;other conditions are thermal /hydrothermal alteration and gravity that influence seismic slip).

CONCLUDING REMARKS

There is a stormy debate in the geosciences regarding the role of microstructures of a fault, as suitable tools for assessing seismic deformation. The present study shows that the evidences of rock deformations, an important input in understanding basic processes associated with fault geometry and composition, by very complex physical processes, are preserved in microstructural features of fault rocks. Grain scale geometry of deformed particles discussed in this study not only helps to estimate the level of seismo-tectonic occurrences but also indicates the pattern of stress and direction of slip at micro level. From that stand point two physical parameters can be used for analysing the nature of early seismo-tectonic occurrences:

(i) impact of complex stress on grain scale geometry modification

(ii) impact of fluid flow on seismic slip.

Apart from that the study also shows the possibility to predict the increase of regional level stress by regular monitoring of the grain geometry modifications and changes of fluid behaviour in an active fault zone. Although, the result worked out through the above mentioned process of laboratory testing is satisfactory, more in-depth study on fault rock microstructure is needed to substantiate the present results. Regular seismic data generation and crustal deformation mapping by establishing permanent monitoring stations, equipped by seismic recorders and satellite technologies like Geodetic GPS in some selected places are needed for understanding the accuracy of microstructural study in assessing the seismic events.

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