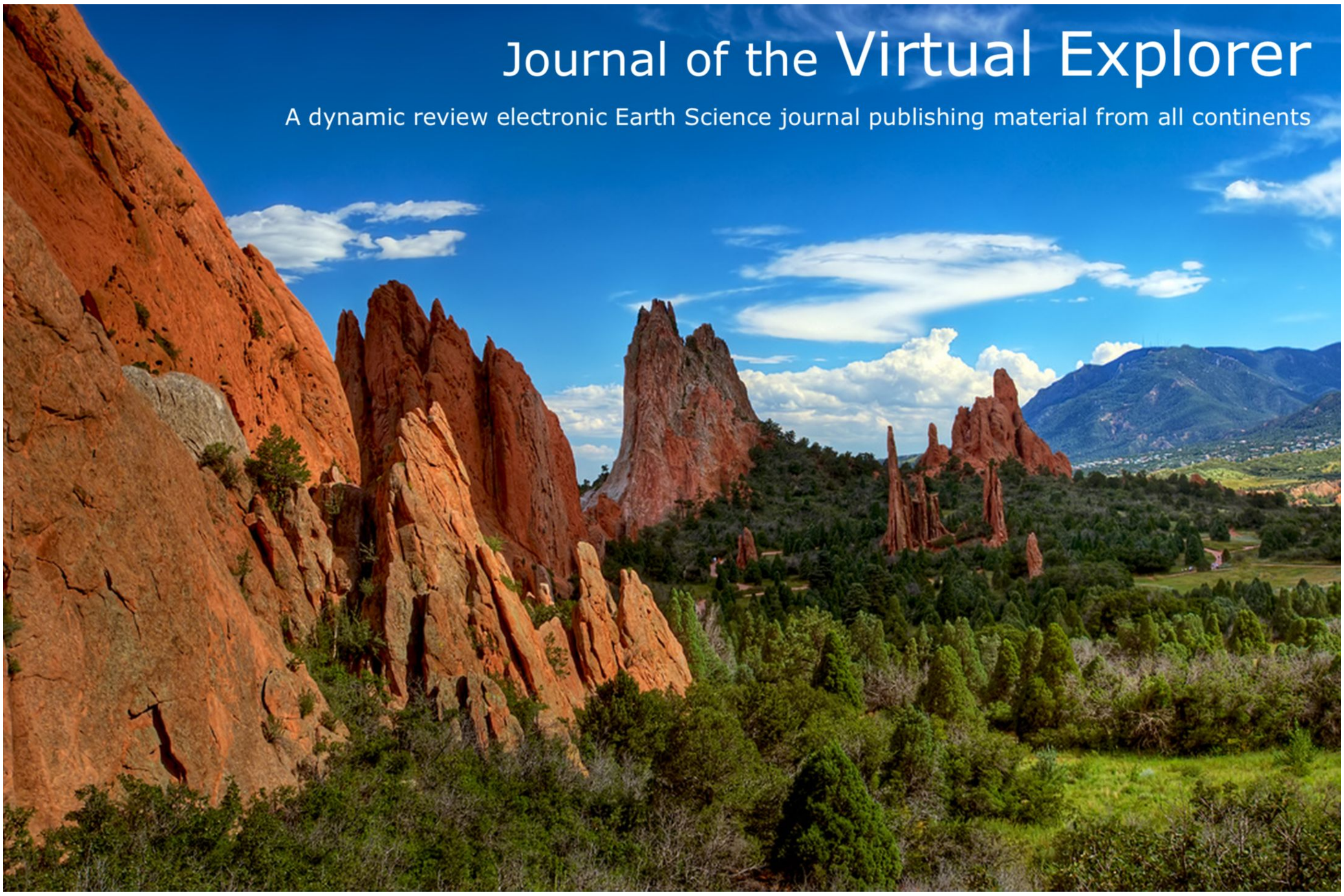

Repeated cataclasis in a reactivated fault zone -- an example from Bengal Basin Margin Fault, Jharkhand, India

Abdul Matin, Surajit Misra

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **32**, paper 6
In: (Eds.) Talat Ahmad, Francis Hirsch, and Punya Charusiri,
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Abstract: Fault zones with a complex history may show reactivation in successive faulting events. Successive generations of grain-scale microcracks in reactivated fault zone produce multiphase cataclastic rocks with characteristic microcracks. The optical and cathodoluminescence microscopic study can be fruitfully utilized to analyze the complex deformation history of brittle fault zone rocks developed in response to successive brittle deformation. Within the reactivated Cretaceous Sainthia-Brahmani Fault, cutting the Precambrian Chhotonagpur gneiss and Jurassic sandstone along the western margin of Bengal Basin, three generations of cataclasis can be recognized. The first generation (Ct1) cataclastic rock is infrequently preserved as clasts within the second phase (Ct2) cataclastic rocks. The last phase cataclasis (Ct3) affected both Ct1 and Ct2 cataclastic rocks in a discrete manner producing inhomogeneous network of thin sintered micro-zones of gouge. The cataclastic rocks are formed by progressive cataclasis of granitoid rocks with several pulses of fluid-induced brittle deformation during a history of frictional flow. The repeated cataclasis attest to a prolonged history of repeated failure and reactivation of fault movement in elastico-frictional regime operated in pulses with repeated embrittlement and mechanical failuret. This observation led to the idea of repeated reactivation of the fault, related to the extensional tectonics during early Cretaceous period linked to India's passage over the Kerguelen and Crozet Hot-Spots presently located in the Indian Ocean. Fracturing and comminution are dominant deformation mechanisms in the formation of cataclastic rocks, and subordinate but evident dissolution and recrystallization of quartz, and mild plastic deformation of quartz, feldspar and biotite are also seen. Dissolution and recrystallization processes during cataclasis, and absence of pseudotachylyte in the fault rocks provides an example of aseismic shear displacement within the brittle shear zone.

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Paper Review

This paper is in dynamic review. Readers may email commentary to: <team@virtualexplorer.com.au>.

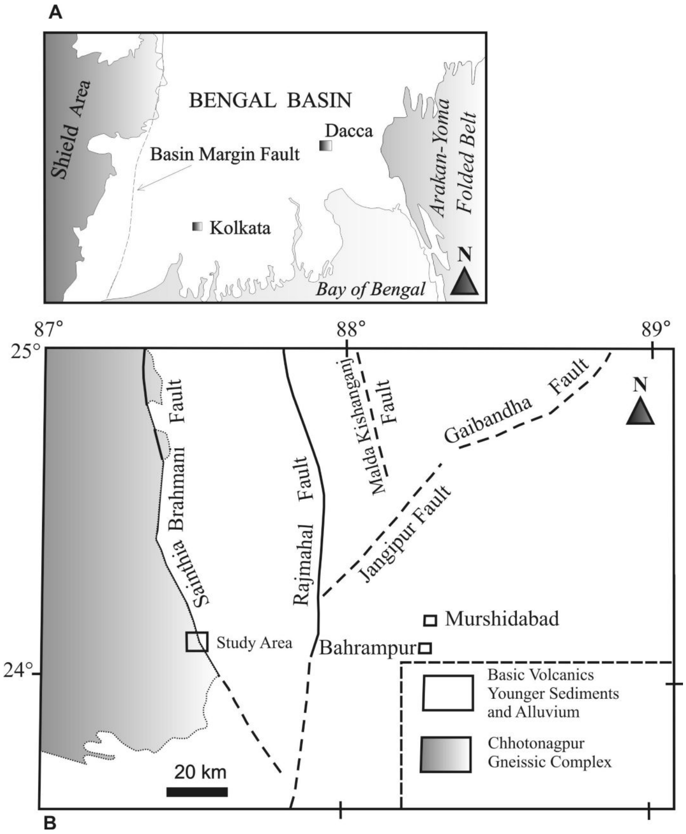
Introduction

Cataclastic rocks are commonly formed in the shallower part of the brittle continental crust, above the elastico-frictional to quasiplastic (EF-QP) transition (Sibson, 1977; Snoke *et al.*, 1998). The rocks in the continental crust at shallow crustal depth deform by brittle fracturing and cataclastic flow due to increase of shear strength with confining pressure in the cataclastic domain of deformation by the operation of Coulomb frictional law (Byerlee, 1978). Fault gouges and cataclastic rocks are common products of rock fracturing in the cataclastic domain (*e.g.* Sibson, 1977; Passchier and Trouw, 2005). Cataclasis is the deformation mechanism to produce cataclastic rocks in fault zone (the term *cataclasis* is used here following Rutter, 1985 - "crystal structure remains undistorted, but grains or groups of grains become cracked and the fragments may exhibit frictional sliding with respect to one another" and "the process necessarily involves dilatancy and is therefore pressure sensitive").

Large scale brittle faults at shallow crustal depths are characterized by localized intense deformation in thin zones (Sibson, 1977). Field exposures, hand samples and thin sections show intensely deformed silicified cataclastic rocks are developed in the Bengal Basin margin Sainthia-Brahmani Fault (SBF) in West Bengal and Jharkhand state (Fig. 1). Fault rocks are very well exposed along the SBF for hundreds of meters with thickness reaching up to several meters. We present here an example of repeated cataclasis and meso- and micro-structures of brittle fault rocks. The deformation within a "fault zone" (Sibson, 1977) with prolonged tectonic history involving successive episodes of microfracturing due to fault reactivation during progressive deformation in an elastico-frictional (EF) regime is also discussed. Our observation shows that comminution, dissolution-recrystallization and mild plastic deformation were involved in the generation of cataclastic rocks.

Ductile structures developed in quasi-plastic deformation regime have been extensively investigated and effectively used universally to understand the deformation history and deformation kinematics, however, the use of cataclastic structures in understanding those points is not commonly attempted.

Figure 1. Bengal Basin with Basin Margin fault



(A). Bengal Basin with Basin Margin fault along its western boundary. (B). Disposition of faults in the Bengal Basin including the basin margin Sainthia-Brahmani Fault and study area (marked with box) (after Dasgupta and Mukherjee, 2006, and Dasgupta *et al.* 2000)

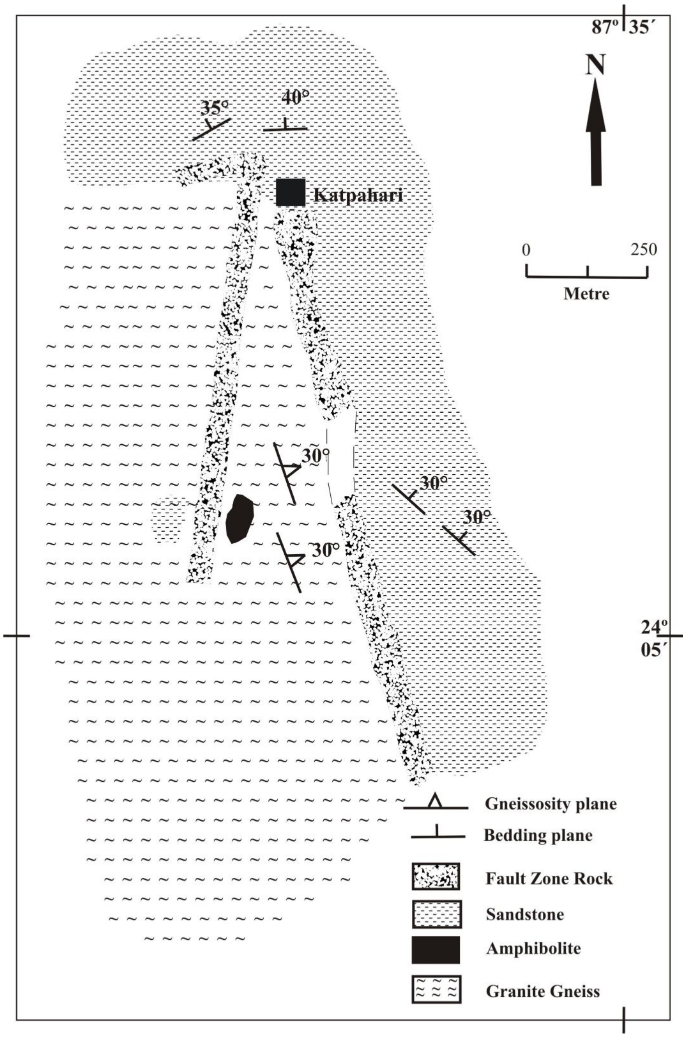
Geological setting

The Bengal Basin is bordered by Precambrian Chotanagpur gneissic terrain in the west and northwest (Dasgupta *et al.*, 2000; Dasgupta and Mukherjee, 2006) (Fig. 1). Bengal basin margin fault in the west demarcates the Chotanagpur terrain in the west and a sequence of early Permian to early Triassic coal bearing Gondwana rocks, Jurassic Dubrajpur Formation and Cretaceous Rajmahal flood basalt in the east (Fig. 1). This fault, named as Sainthia-Brahmani Fault (SBF) (Dasgupta *et al.*, 2000) developed following the western and northwestern margin of the Bengal Basin. SBF and other faults further east of SBF (Fig. 1) (*e.g.* Rajmahal Fault, Dasgupta *et al.*, 2000) are genetically related to the extensional tectonics prevalent over this region during the early Cretaceous period and may have been related to the Rajmahal effusion linked with India's passage over the Kerguelen and

Crozet Hot-Spots presently located in the Indian Ocean (Nandy, 2001; Dasgupta and Mukherjee, 2006). The age of SBF is not certain but definitely it was active till post-Jurassic time since it has affected the Jurassic Dubrajpur Sandstone. Fault rocks are well exposed along the SBF of the study area (Fig. 1) and are typically represented by strongly fractured and hydrothermally altered cataclastic rocks encompassing 'layers' of silicified fault breccia or fault gouge (terminology after Sibson, 1977).

The area of study is underlain by the rocks of Chotanagpur granite gneiss with enclaves of amphibolite partly covered by Dubrajpur Sandstone. There are three 'bands' of fault rocks – two of which have N-S trends exposed over a length of ~1 - 1.5km, and the third one has a E-W trend exposed over a length of ~250m (Fig. 2). Maximum thickness of the fault rocks goes up to ~20 meters. In Chotanagpur granite gneiss foliation is pervasively present with more or less uniform orientation, while in cover sediments bedding shows variable orientation (Fig. 2).

Figure 2. Map of the area



Geological map of the area of study.

Outcrop, hand-sample and microstructure observations

Country rocks

Chotanagpur Granite gneiss is usually strongly foliated; foliation is defined by compositional banding with alternate quartz-feldspar rich- and biotite-hornblende-rich, mm- to cm-scale bands. The rock is coarse grained (1mm and more in grain size), leucocractic and consists of quartz, feldspar, and mafic minerals. It is fractured and fracture planes are commonly healed by silica and iron oxide.

Quartz and plagioclase feldspar constitute ~90% of the granite gneiss. Microcline is present in small amounts. Mafic minerals, such as amphibole and biotite and opaque minerals together constitute ~10% of the rock. Most of the quartz grains show weak to strong undulose extinction with some showing occasional deformation lamellae. Some grains show subgrain rotation recrystallization (Twiss and Moores, 1992). Plagioclase grains are commonly altered to different degrees and appear cloudy in plane polarized light. Amphibolite enclaves occur in isolated outcrops within the granite gneiss. They are massive, hard and consist of hornblende (>60%) and plagioclase with subordinate clinopyroxene and quartz (~15%).

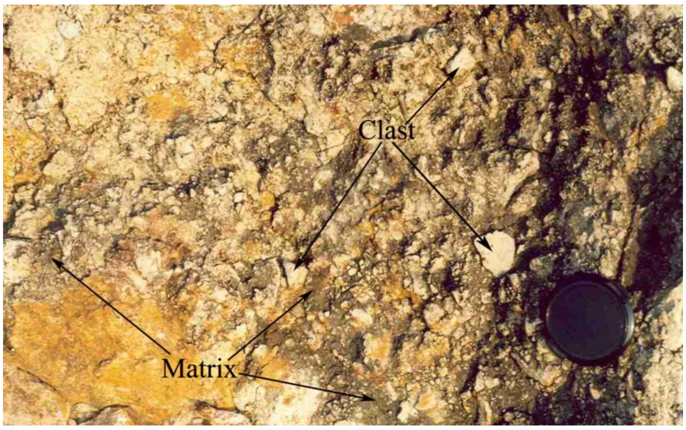
Massive to well-bedded, coarse-grained, clast supported Dubrajpur Sandstone consists of quartz (>95%) as dominant framework grains with fairly uniform grain size. Strong undulose extinction and subgrain in some quartz clasts suggest deformed provenance. Thin bands of conglomerate are locally present within sandstone. Fracture and joint planes are quite common in all types of rocks including fault rocks.

Fault rocks

Outcrop and hand samples

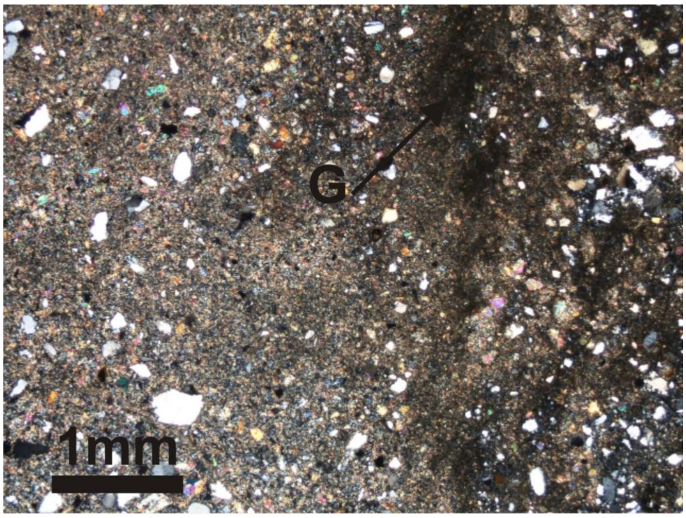
Fault rocks occur along three linear ridges (Fig. 2) represented by cataclasite and gouge (Sibson, 1977). Fractures are common; they are straight to curved and usually healed up by opaque substance that gives rise to distinct deep brown to black colour in outcrops (Fig. 3). The fractures are neither uniformly distributed, nor uniformly oriented, at least on the scale of the exposure; the cataclastic rocks almost always give the impression of having an isotropic cataclastic fabric (Fig. 3). The rock is composed of light-coloured sub-angular to rounded fragments of granitic and sandstone protolith embedded within the fine grained, dark- to light-brown coloured matrix (Fig. 3). The transition of cataclastic rock to the host rock is sharp or progressive where the cataclastic rock band is bordered on both sides by coarser cataclastic rocks in fault related deformation zone.

Figure 3. Massive cataclastic rock in outcrop



Field photograph showing massive cataclastic rock with clasts of different shape and size (light colour) embedded in a fine grained iron oxide-rich darker matrix.

Figure 4. Microbreccia with clast-in-matrix texture



Photomicrograph of microbreccia showing angular to subrounded clasts of single crystals and rock fragments surrounded by matrix of extremely fine rock flour. G, Gouge. Crossed polars.

The fault rocks are indurated, cohesive, massive, hard, compact, and non-foliated (Fig. 3) cataclasites and ultracataclasites in the fault zone. They have low specific gravity and are commonly ochre-yellow to dark brown on weathered surface due to stain of iron oxide solution and off white to light brown on fresh exposures (Fig. 3).

Microstructures

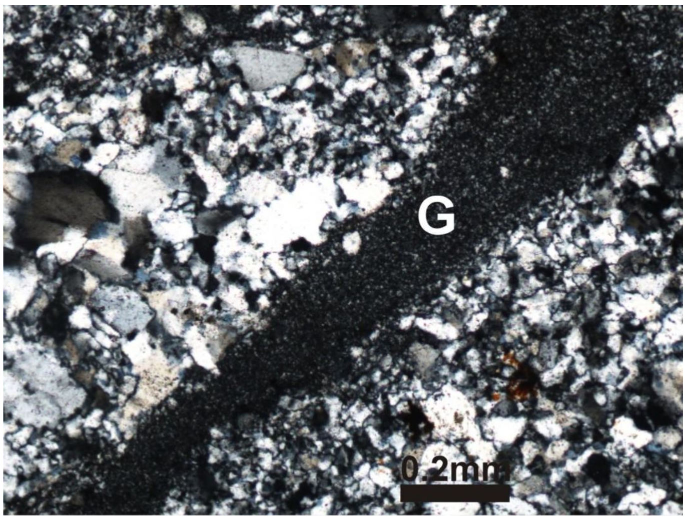
At grain-scale, the diagnostic character of the fault rocks is the clast-in-matrix texture and the clasts or survivor grains are surrounded by a matrix of finer comminuted grains and secondary minerals. Clasts are derived from the host granodiorite gneiss, but occasional clasts from Dubrajpur sandstone are seen. The clast-in-matrix texture can be further subdivided into cataclastic and granular textures (*cf.* Twiss and Moores, 1992). The microstructures were studied using polarized optical microscopy and cathodoluminescence microscopy. These techniques were useful in separating several generations of microfracturing based on their morphology and cross-cutting relationships. Details of cataclastic rocks can only be seen under microscope.

Angular blocks of material with more finely comminuted material, produces an originally cohesionless mass known as fault breccia or microbreccia where the largest fragments are up to about 5cm. in length in the fault rocks. When the comminuted material is granulated to fine flour of rocks (0.1 to 100μm in size) the product is known as gouge (Sibson, 1977; Scholz, 1990). Both breccia and gouge are cohesionless material but they become impregnated and sealed by crystal growth of silica in the voids to produce cemented breccia or cemented gouge (Stel, 1981). In the present work, classification of Sibson (1977) and Scholz (1990) has been followed to name the fault rocks.

The fault rock dominantly (more than 90%) consists of large and medium size clasts of quartz, feldspars and rock fragments (length varies from 0.02mm to 2.8mm and width from 0.01mm to 1.80mm but the majority of the clasts are 1 mm or less). Largest clasts are usually of rock fragments. The clasts are embedded in a fine grained groundmass that consists of smaller grains varying in size from less than 0.01 mm to 0.85 mm (Fig. 4). Locally gouge is present as irregular bands and patches (Fig. 4). Opaque clasts are commonly present as isolated grains; patchy aggregates of fine grained opaques are also present within the groundmass and along the boundary of the large clasts.

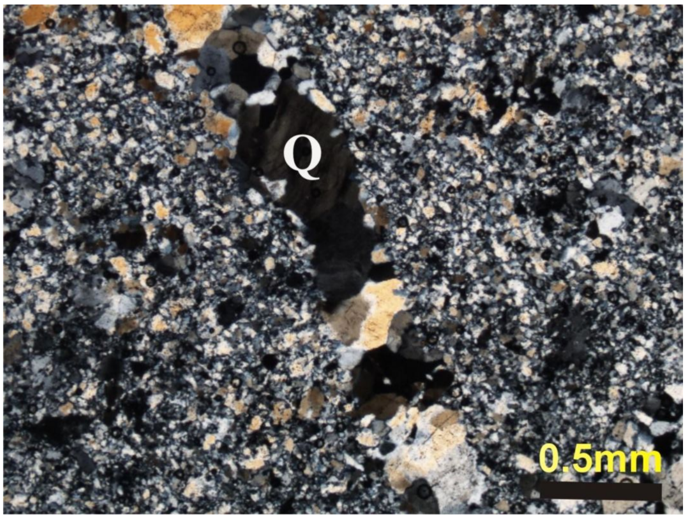
There is a fair amount of heterogeneity in the size of the clasts and it varies widely from one exposure to another and this can be observed even in micro-scale. Most of the clasts are highly angular, squarish to sub-squarish, elliptical or triangular or rectangular in shape and commonly show strong undulose extinction and incipient recrystallization. Groundmass dominantly consists of very fine grained to submicroscopic cataclastic material with secondary silica that appears as dark aphanitic mass under optical microscope. Fine grained flour material of cataclastic rocks (gouge) is mostly aphanitic and commonly occurs as narrow discontinuous bands transecting across early cataclastic rocks (Fig. 5) and also along fractures in large clasts. Width of these gouge zones varies from less than 0.02mm to 2.2mm. Isolated relatively large clasts are occasionally present in gouge. On the basis of the percentage of matrix majority of the cataclastic rock belongs to cataclasite (matrix 50-90%), although it varies from protocataclasite (10-50% matrix) to ultracataclasite (<90% matrix) (Sibson, 1977; Scholz, 1990). Thin pressure solution seams are present in gouge zones. Once the finer material reduces below a certain grain size pressure solution become an important mechanism of deformation. Fractures in cataclastic rocks are often filled up by quartz veins (Fig. 6), and the groundmass of the cataclastic rocks is always silicified. The silicification of cataclastic rock has produced silicified cataclasite. In some cases, the highly fractured masses of fine grained quartz resemble dynamically recrystallized quartz, but deformation is dominated by brittle processes as suggested by Evans (1988). The silica of the groundmass remains dark in plane polarized light and are otherwise unobservable if not seen using cathodoluminescence (Figs. 7a and b).

Figure 5. Late phase gouge on early cataclastic rock



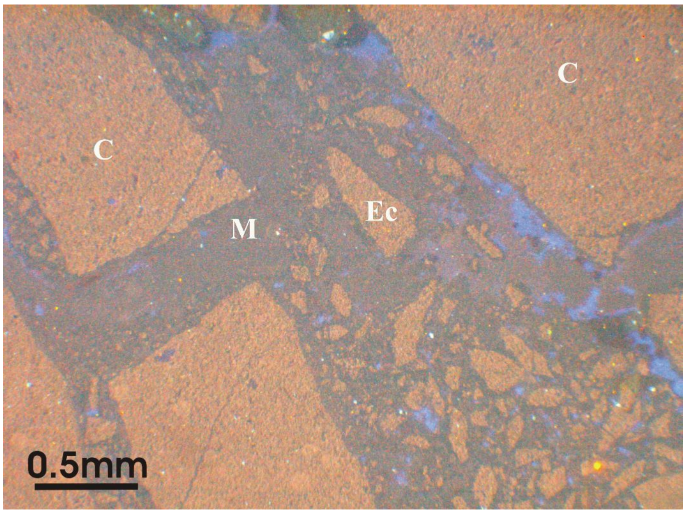
Photomicrograph of microbreccia showing fine-grained to submicroscopic cataclastic rock (gouge, G) formed on coarser-grained cataclastic rock along thin micro zones (G). Crossed polars.

Figure 6. Silicified breccia



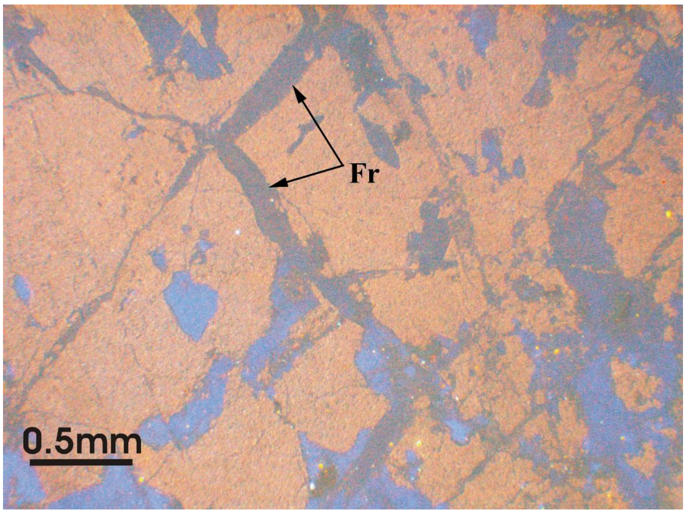
Photomicrograph of silicified breccia showing fracture filled with quartz crystals which show signature of plastic deformation suggesting deformation continued after silicification. Q, quartz crystal. Crossed polars.

Figure 7a. Cathodoluminescence image of silicified cataclastic rock



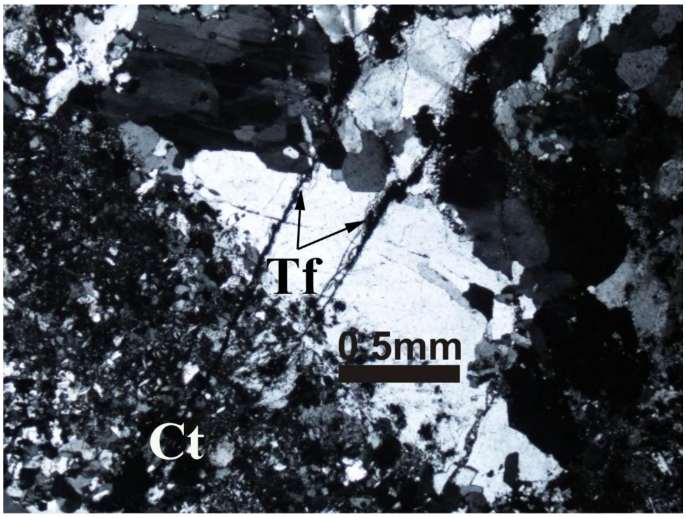
Microfracture zone consists of randomly oriented smaller clasts (Ec) of varying size and shape floating in a silicified (M, dark grey and blue) submicroscopic matrix. Healed intragranular extension fractures occur in large clasts (C). Note the very sharp boundary of the fracture zone with clasts.

Figure 7b. Cathodoluminescence image of silicified cataclastic rock



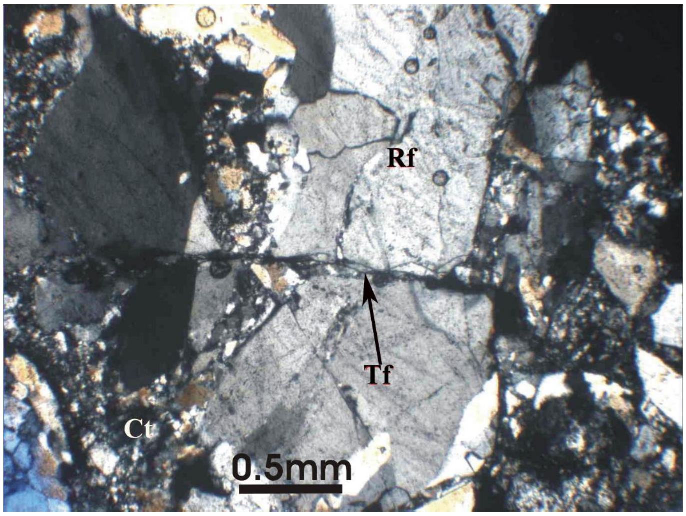
Showing conjugate set of fractures (Fr) healed by silica (dark grey and blue). Note that later generation intragunalar shear cracks displace older silica vein (lower left corner). Crossed polars.

Figure 7c. Photomicrograph of breccia with transgranular fracture



Showing cataclasite zone (Ct) bordered by wall rock affected by transgranular fractures (Tf) lined by thin cataclasite zone cutting across older silicified cataclastic rock layer suggesting multiple phases of cataclasis. Crossed polars.

Figure 7d. Photomicrograph of breccia with transcrystalline shear fracture



Showing intergranular, continuous transcrystalline shear fracture (Tf) across large clast. Fractures are lined by thin cataclasite zone. Rf, rock fragment; Ct, cataclastic zone. Crossed polars.

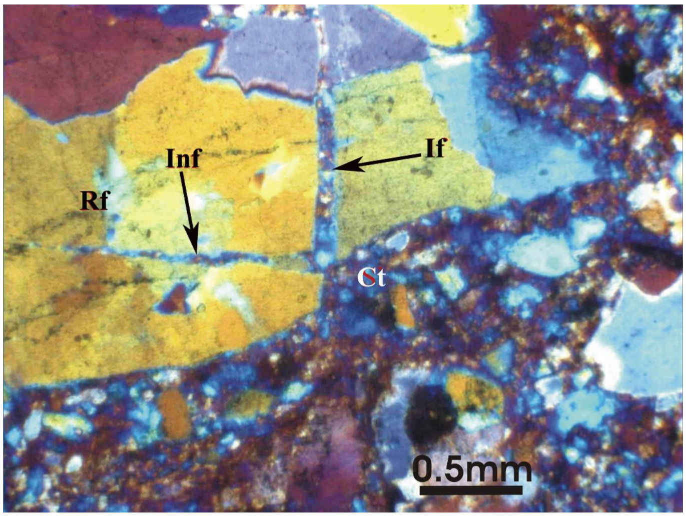
The cataclasis is visible as a network of cracks, sometimes straight and sometimes less regular. The microfractures die out within a short distance (intragranular cracks) or continue for a long distance as grain boundary cracks or intergranular cracks. Fractures are ubiquitous within the clasts as well as in groundmass. Fracture density varies from grain to grain. The microcracks may be unhealed fractures but commonly they are healed (Figs. 7a-d). The fractures are branching at places and comminuted subgrains are rotated along fractures (Figs. 7a, d).

A variety of different crack geometries, morphologies and orientations are developed in the fault rocks. The cracks may be broadly divided as intragranular cracks (contained within single grains) and intergranular cracks (Figs. 7c, 7d) (within a length of several grain diameters) (Kranz, 1983; Ismat and Mitra, 2001; Passchier and Trouw, 2005). They are typically blunted at grain boundaries, either because they run into a more ductile matrix or because they impinge on a grain with a suitably oriented glide system that allows the stress concentration to be dissipated (Mitra, 1978). Intragranular cracks formed under dominantly plastic deformation conditions are crystallographically controlled and may not be directly related to regional stresses. Other intragranular cracks that formed during initial fracturing under cataclastic conditions develop only in grains that are optimally oriented to the deforming stress (Ismat and Mitra, 2001). This type of deformation results in grain-size reduction in a thin deformation zone in rocks. Intragranular cracks having the same orientation in many grains suggest that they are brittle and result from far-field stresses that also produced the large transgranular cracks (Ismat and Mitra, 2001). These cracks suggest increasing deformation resulting in coalescence of some cracks to form a single, continuous fracture (Figs. 7c, 7d).

Intergranular cracks range in length from a few grain diameters to continuous fractures in the rock (Figs. 7c, 7d). Transcrystalline fractures (fractures running through several grains) are lined by finer cataclasite associated with more intense deformation (Figs. 7d, 8). They generally form under elastico-frictional deformation conditions under which cracks, once nucleated, can coalesce with other cracks or propagate unstably due to stress concentration at crack tips. These types of cracks have been described as Brittle Intergranular Fracture type 1 (BIF1) (Gandhi and Ashby, 1979; Ashby *et al.*, 1979; Atkinson, 1980) and have been previously described from quartzites (Lloyd and Knipe, 1992). Crack propagation is blocked by higher pressure and is also controlled by material inhomogeneities. If the matrix has lower fracture strength than framework grains cracks tend to nucleate at grain-grain contact or grain-matrix interfaces and propagate along grain boundaries (Ismat and Mitra, 2001). If there is no strength difference between framework and matrix, cracks may nucleate within framework or matrix, and can propagate across grain-boundaries and through successive grains (Fig. 7c); these intergranular cracks are referred to as transgranular cracks (Ismat and Mitra, 2001).

In zones of strong deformation, smaller framework grains show particularly strong undulose extinction while larger grains are fractured. These fractures developed typically at dislocation pile-ups and are oriented at high-angles to glide planes. They are intragranular cracks and lead to reduction of grain size in the rock (Fig. 8). There are healed shear cracks with grain boundaries and twin lamellae offset along them (Fig. 7d).

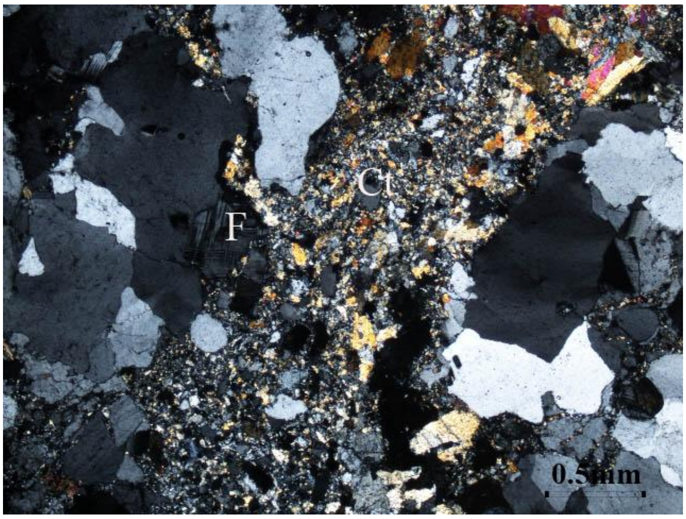
Figure 8. Silicified cataclasite zone



Photomicrograph of breccia with gypsum plate showing intensely fractured silicified cataclasite zone (Ct) and less deformed wall rock (Rf) contains conjugate set of fractures (If and Inf) lined by thin cataclasite zone. Note the sharp angular boundaries of the clasts. Crossed polars.

Wider intergranular zones of fine-grained cataclasite, which completely reformed the original grains, show microstructures resembling sintered material (Anderson *et al.*, 1974). Extremely fine-grained (approximately 1µm) materials of the reformed grains show interlocking grain boundaries in some sections (Fig. 9). Because of their fine grain-size and three dimensional interlocking nature the boundaries often appear a little fuzzy under the microscope (Fig. 9). The development of intergranular and anastomosing cracks, usually parallel to cataclastic zone boundaries, indicate that these zones grew in thickness by fracturing in adjoining rocks to reduce asperities at the wall rock–cataclastic zone boundary (Mitra, 1984). Transgranular cracks that branch from cataclastic zones are observable in thin sections. Later phase cracks crosscut the previous features as well as matrix in wider cataclasite zones.

Figure 9. 'Penetrative' transgranular sintered zone



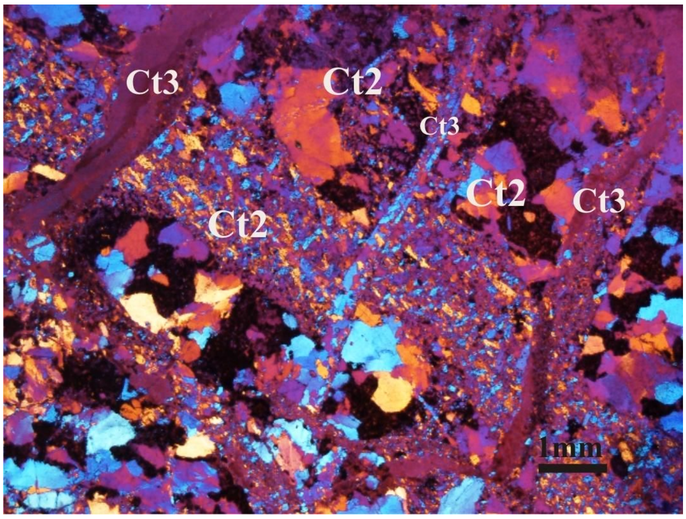
Photomicrograph of breccia showing wider 'penetrative' transgranular sintered zone (Ct) of interlocking fine-grained cataclastic zone which completely reformed the original grains. F, feldspar. Crossed polars.

There are also thick (up to 2mm) microzones of cemented cataclasite with angular, randomly oriented fragments that probably grew from thinner zones by incorporating angular fragments from the wall rock into the zones (Fig. 7a). Under elastico-frictional deformation conditions, the finer-grained matrix is stronger than the framework, and microcracks are likely to grow from pre-existing flaws within the framework grains (Fig. 7a) (Cleavage I cracks of Gandhi and Ashby, 1979), and only in those grains that contains flaws that are in suitable orientation to grow under the externally applied stresses (Sussman, 1995).

Length of the fractures varies from 0.23mm to more than 4.5mm and width of the fractures zone within grains (crushed zone within grain due to grain crushing, *e.g.* Figs 7a and 8) varies from less than 0.04mm to 0.05mm. Conjugate set of fractures in clasts are common (Figs. 7b, 8) with varying width from 0.01mm to 0.09mm. They are mainly intergranular to transgranular. These fractures are continuous, transecting, cutting across cataclastic mass through the clasts (Figs. 7b, 7c) sometimes irregular in their orientation, branching and often coalescing and are healed by silica and iron oxide precipitations (Figs. 7a-c). Fractures vary from straight, wavy, sharp to zigzag in pattern following the cleavage planes of feldspar grains. Under cathodoluminescence, the sealing of fractures by silica is very distinct; and it is observed that almost all the fractures are healed up by silica irrespective of their thickness and nature (Figs. 7a, 7b).

At places the fractures are lined with thin films of gouge consisting of very fine-grained, floury crushed silicified material (Figs. 7a, 7c, 7d). Thin micro gouge zones developed on older cataclasite; thickness of these zones varies from 0.2mm to 3mm (Figs. 5, 10).

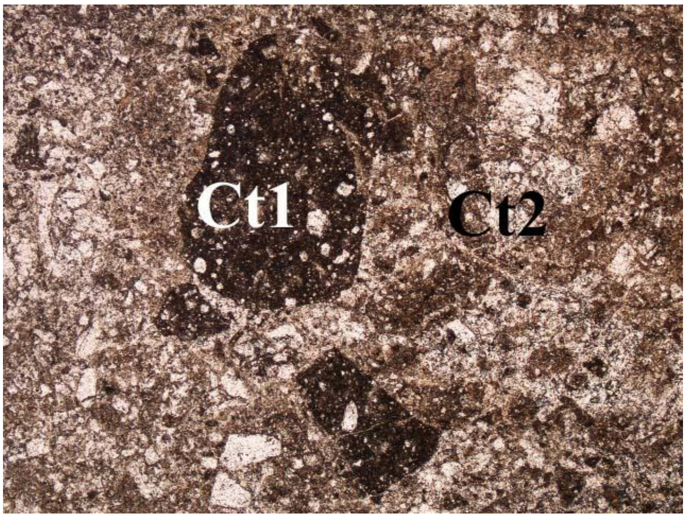
Figure 10. Multiple phases of cataclasis



Photomicrograph of intensely deformed silicified cataclastic rock showing multiple phases of cataclasis. The later cataclastic rock zone (Ct3) with sharp boundaries cutting across older cataclastic rock (Ct2). Please note that in the central part the Ct2 zone is displaced along Ct3. Crossed polars with gypsum plate.

The cataclastic rocks show recataclasis of earlier cataclastic rock. The repeated cataclasis is marked by the following evidences: a) clasts of older cataclastic rock is present within younger cataclasite (Fig. 11), and b) the older cataclasite is further crushed and granulated by fracturing and thin gouge zones running across the older cataclastic mass affecting both the matrix and the clasts (Figs. 5, 10). These gouge zones and films are formed in high strain zones suggesting strain partitioning in microscale. All these features suggest brittle on brittle deformation.

Figure 11. Clasts of older cataclastic rock within later cataclastic rock



Photomicrograph of reactivated cataclastic rock showing clasts of older rounded to subangular clasts of earlier cataclastic rock (Ct1) embedded by later cataclastic rock (Ct2).

Succession of tectonic events

From microstructural investigation, it is inferred that at least three stages of cataclasite generation can be distinguished in the fault rocks of SBF. The time gap between these stages of generation cannot be estimated.

The first phase (Ct1) cataclastic rock is further subjected to cataclasis along with the country rocks to form second phase (Ct2) cataclastic rock which contains fragments of older cemented cataclastic rock fragments of Ct1 along with other rotated angular fragments embedded within the groundmass of Ct2 (Fig. 11). The Ct1 and Ct2 are further subjected to third phase (Ct3) cataclasis.

Character of different phases of cataclasite

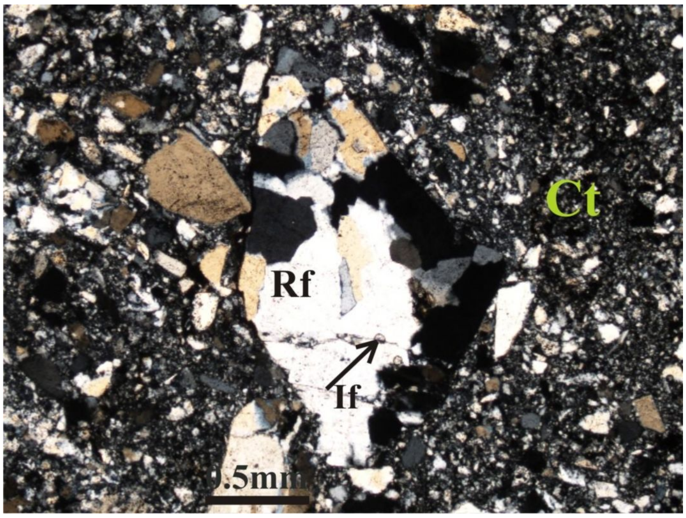
Ct1

It occurs as clasts of Ct1 cataclasis embedded within later phase (Ct2) cataclastic rocks (Fig. 11). This is the oldest identified cataclastic rock consisting of comminuted angular to sub-rounded clasts of quartz and occasionally feldspar (up to 0.2mm in dimension) in a fine dark groundmass (Fig. 11). The fine darker groundmass of Ct1 constitutes >60% of the rock. Major part of the groundmass is aphanitic and consists of dark submicroscopic material composed of secondary silica and iron oxide introduced into the matrix by iron oxide rich solution (Fig. 11). Shapes of the Ct1 clasts are rounded to sub-rounded, rectangular to elliptical to circular and also irregular. The rounded and sub-rounded clasts of Ct1 suggest that the older clasts are abraded by subsequent cataclasis. The proportion of darker substance (iron oxide) in Ct1 is much higher than in Ct2 and that makes it sharp and distinct within Ct2 (Fig. 11). The Ct1 became fairly cohesive due to impregnation of silica and iron oxide and that helps it to take part as hard material in later phase cataclasis. Clasts of remnant Ct1 is not present everywhere because they are possibly destroyed by subsequent cataclasis.

Ct2

In the entire fault rock this phase of cataclasis is most dominant and controls the micro structure of the fault rock. Clasts are dominantly quartz with substantial amount of rock fragments and a few feldspar and muscovite clasts set in a matrix dominantly made of silica and smaller amount of iron oxide (Figs. 4, 7c, 9). The matrix varies in proportion from place to place and the cataclastic rock is protocataclasite to cataclasite proper and rarely ultracataclasite. The proportion of clast to matrix varies from more than 80% to less than 10%. The size of the clast fragments varies from large to quite small (Figs. 4, 12). Matrix is dominantly made up of fine material often submicroscopic with small clasts of quartz and rarely feldspar. The aphanitic part of the matrix contains secondary silica which has percolated into the cataclastic groundmass to form silicified cataclasites. The degree of crushing varies within a short distance. Somewhere large protolith fragments (0.2mm to 10mm in length and 0.15mm to 7mm in width) are present (Fig. 12). In microscale large clasts and intact protoliths are penetrated by narrow, continuous to discontinuous, coalescing cataclasite zones of variable thickness forming a network of fractures within protolith (Fig. 8). Clasts of older cataclastic rock (Ct1) are remarkably well preserved at places (Fig. 11).

Figure 12. Relict of rock fragment clast within cataclastic rock



Photomicrograph showing intensely deformed cataclastic rock with remnant of large rock fragment (Rf) with a fewer number of intergranular fractures (If). The matrix (Ct) consists of very fine to medium size angular crystals of quartz and submicroscopic material in cataclastic rock. Crossed polars.

In some Ct2 pressure solution in fine-grained matrix concentrates insoluble opaque material into thin microseams which eventually run together to form a thicker opaque zone. These opaque zones at places show preferred orientation to define a crude foliation. The foliation swings around coarse clasts of quartz and feldspar. Silica veins often form comb structure where quartz crystals grow from the wall towards the centre. The silica veins are fractured by later cataclasis with thin films of gouge along the fractures. These gouge-lined fractures are developed during third phase (Ct3) cataclasis.

Ct3

The last phase of brittle deformation is present as thin, lensoid, isolated patches of gouge and networks of fractures lined with gouge developed on Ct1 and Ct2. At the grain scale, thin open cracks and thin zones of coherent gouge formed, cross-cutting all previous features (Figs. 5 and 10). The cracks are generally healed and stained with iron oxide. The gouge and fractures are developed in the matrix of Ct2 and in the clasts of Ct1 as thin short micro zones and "films" during this phase of cataclasis and thickness of the zones is from up to a few mm to fraction of a mm (Figs. 5, 10). The boundary of Ct3 with Ct2 is sharp to gradational and straight to wavy (Fig. 5) It consists dominantly of aphanitic submicroscopic material impregnated with very fine clasts of quartz (Fig. 5 and 10). Thin pressure solution zones are present as discontinuous seams in gouge zones developed due to further straining of very fine clasts.

The nature of deformation in all the fault rock bands is similar, but not all phases of brittle deformation are equally well preserved in all bands. The last two phases are commonly visible in all the bands but the evidence of earliest phase is rarely preserved. We interpret that all these features are formed at low temperature at shallow crustal depth and associated with the faulting along Bengal Basin margin SBF.

Microstructures and deformation mechanisms

The cataclastic rocks encompass the whole spectrum between clast-supported protocataclasite (matrix <10%) and matrix-supported ultracataclasite (matrix ~90%). There is a general decrease in the size and increase in roundness of clasts and increase in matrix proportion when passing from protocataclasite to ultracataclasite. This observation suggests the increasing importance of cataclasis, which consists in microfracturing and microbrecciation of quartz and feldspar crystals, together with intergranular sliding and rotation of the resulting fragments as suggested by Fabbri *et al.* (2000). Although cataclasis played the most dominant role in the evolution of this fault rock diffusive mass transfer also played a subordinate but important role in the genesis of cataclasite. The signature of dissolution is stylolite-like surfaces crossing clasts of quartz and, in some instances, the matrix. Along with mechanical cataclasis, recrystallization of the dissolved material occurred in the matrix part where aphanitic silica precipitation is pervasive. In the matrix dominated cataclasite the long clasts show a tendency to be aligned preferentially indicating occurrence of flow in matrix-supported cataclasite.

The mechanisms of deformation which led to the formation of the randomly oriented cataclasite are faulting, cataclasis, and diffusive mass transfer processes. The dark seams, in fact, consist of residual accumulations of insoluble biotite and iron oxides. Newly recrystallized polygonal quartz grains or subgrains surround larger quartz or feldspar crystals and fill the intragranular fractures spaces in a similar way described by Hippertt and Egydio-Silva (1996). Plastic deformation mechanisms played a subordinate role in the process and are represented by undulatory extinction, recrystallization and subgrain formation of quartz grains and sigmoidally bent biotite crystals. Silicification is pervasive and all samples studied under cathodoluminescence show silicification along fractures down to hairline cracks.

Discussion and conclusion

Fault zones with complex and prolonged deformation histories may be reactivated during successive deformation episodes, because they represent distinct weaker inhomogeneities in the country rock of undeformed material. In the reactivated zones, superposition of multiple cataclasis events occurs in an irregular way. Detailed microstructures of the finite product of cataclasis provide an important tool for identifying the superposition of successive events of deformation with the help of morphology and consistent cross-cutting relationships of different generations of microcracks and cataclasis (Ismat and Mitra, 2001).

Pseudotachylite has not been observed in this fault rock. There are no unambiguous criteria which could help in deciding whether a cataclastic rock formed during seismic or aseismic slip (*e.g.* Cowan, 1999). Energy balance for mechanical cataclasis is less quantified than for pseudotachylite (Fabbri *et al.*, 2000) and the importance of dissolution and recrystallisation processes seen in the fault rocks in SBF suggest deformational increments at aseismic rates. Diffusive mass transfer is typically a slow process acting at strain rates of about $10^{-14(?)}s^{-1}$ (Shimizu, 1995; Gratier *et al.*, 1999). Therefore it is most probable that cataclasis of the SBF took place under slow, aseismic rates. Since dissolution-recrystallization is typical of slow aseismic strain rates therefore the cataclastic rocks of the SBF zone provides an example of past aseismic slip and aseismic creep in the fault zone.

Within the SBF zone, three generations of cataclasis events can be recognized in the cataclastic rocks suggesting repeated cataclasis in the evolution of the fault rocks. Microstructural evidences of cataclastic rocks have been efficiently used to evaluate fragmentation processes and progressive history of deformation of cataclastic fault rocks. Prolonged cataclastic deformation often accompanied by repeated fracturing and cementation leads to reduction of grain size (Knipe and Lloyd, 1994). The temporal relation of the 'mixed' cataclastic rocks has been determined; however, the length of the different periods in absolute age remains unknown.

Given all this, the role of cataclastic textures and structures in the study of deformation history in elastico-frictional regime may have a significant role in the kinematics of fault movement and therefore, must be better understood to establish a realistic and reliable history.

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