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Clast size analysis of pseudotachylite co-existing with mylonite: Constraints on evolution of Mahanadi Shear Zone, Eastern Ghats Mobile Belt, India

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The Mahanadi Shear Zone (MSZ) in the Eastern Ghats Mobile Belt (EGMB) separates the southern segment of EGMB with dominant NE–SW structural trend from its northern segment with dominant E–W trend. The MSZ is a high-temperature ductile shear zone in which mylonite–ultramylonite occurs intimately associated with pseudotachylite. The association of two components of contrasting origins (ductile and brittle deformations) is possibly attributed to contemporaneous evolution or multiple stages of evolution. Therefore, field and petrographic studies including clast-size analysis of three samples from different localities across the MSZ have been carried out. Field observations suggest that pseudotachylite veins often cut across the mylonitic fabric. In addition, there is variation in orientation of gneissic and mylonitic fabrics in the clasts within the pseudotachylite zones. The pseudotachylites occasionally exhibit crude flow structures and rims around clasts. These features clearly indicate that the mylonitic fabric in the MSZ predates brittle deformation, and the pseudotachylites have not suffered any subsequent deformation after their formation. Clast-size analysis in all three cases follows the Power Law and demonstrates linear distribution. Lower value for fractal dimension ($D = 0.51$–0.69) and involvement of large range of size distribution of clasts in the studied pseudotachylite samples are attributed to brittle deformation at high strain rate, independent of the ductile deformation event. The present study suggests evolution of the MSZ in two stages, i.e., early development of mylonite–ultramylonite by ductile deformation at deeper level followed by pseudotachylite development at later stage by brittle deformation at a shallower level, thereby overprinting of brittle deformation over the ductile deformation.

Keywords. Pseudotachylite; clast; Power Law distribution; evolution; Mahanadi Shear Zone.

1. Introduction

Shand (1916) named a dark coloured aphanitic, volcanic type rock having glassy appearance that occurs as veins and networks in the Parijs region of South Africa as pseudotachylite. This term, in general, has been used to describe all dark looking aphanitic veinlets irrespective of their origin by melting or crushing (e.g., Philpotts 1964; Wenk *et al.* 2000; Lin 2008). The formation of pseudotachylite is attributed to (i) shearing induced crushing and frictional melting during rapid slip

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(Sibson 1975; Spray 1992; Swanson 1992; Lin 1999; Biswal *et al.* 2004; Behera *et al.* 2017; Sarkar *et al.* 2019) and/or (ii) impact melting (Grieve 1975; Bischoff 1982; Reimold and Collision 1992; Spray and Thompson 1995; Pati *et al.* 2015) and rarely to (iii) large landslides (Masch *et al.* 1985; Legros *et al.* 2000). Pseudotachylites have been reported from all types of tectonic environments such as intracontinental fault zones (e.g., Sibson 1975; Magloughlin 1992; Lin 2008), collisional orogenic belts (e.g., Austrheim and Boundy 1994), and subduction zones (e.g., Ikesawa *et al.* 2003; Austrheim and Anderson 2004; Rowe *et al.* 2005). However, more than 95% of pseudotachylite occurrences described in the literature are located within intracontinental fault zones. Since their discovery by Lapworth (1885) and Clough (1888), many studies have investigated the nature and significance of pseudotachylite and the process involved in its formation (cf. Lin 2008).

Co-existence of pseudotachylites and mylonites has been reported from many shear zones (e.g., Sibson 1980; Passchier 1982; Maddock 1992; Camacho *et al.* 1995; Takagi *et al.* 2000; Roy *et al.* 2008; Price *et al.* 2012; Kirkpatrick and Rowe 2013), including the Mahanadi Shear Zone (MSZ) traversing the Eastern Ghats Mobile Belt (EGMB) in eastern India (Mahapatro *et al.* 2009) (figure 1). Conspicuous association of these two components of contrasting origin (ductile and brittle deformations) have been attributed either to single-stage synchronous development during progressive ductile deformation (Passchier 1982; Maddock 1992; Camacho *et al.* 1995; Roy *et al.* 2008; Price *et al.* 2012; Kirkpatrick and Rowe 2013), or multiple stages of evolution.

The kinematics associated with the MSZ is interpreted differently by two groups of workers. While one group opines about extensional movement (Mahapatro *et al.* 2009), the other advocates two different events of movement, viz., initially extensional and later lateral (Bose *et al.* 2020). Mahapatro *et al.* (2009) indicated that the pseudotachylites in the MSZ formed subsequent to ductile shearing at shallow crustal depths without passing into plastic deformation. However, no studies have been carried out to understand the mechanism of pseudotachylite formation in the MSZ. Therefore, to characterize the mechanism and stages of deformation, clast-size analysis of pseudotachylites has been carried out from three different localities across the MSZ in this study. As pseudotachylites serve as an archive and instrument of interpretation for evolution of fault zones

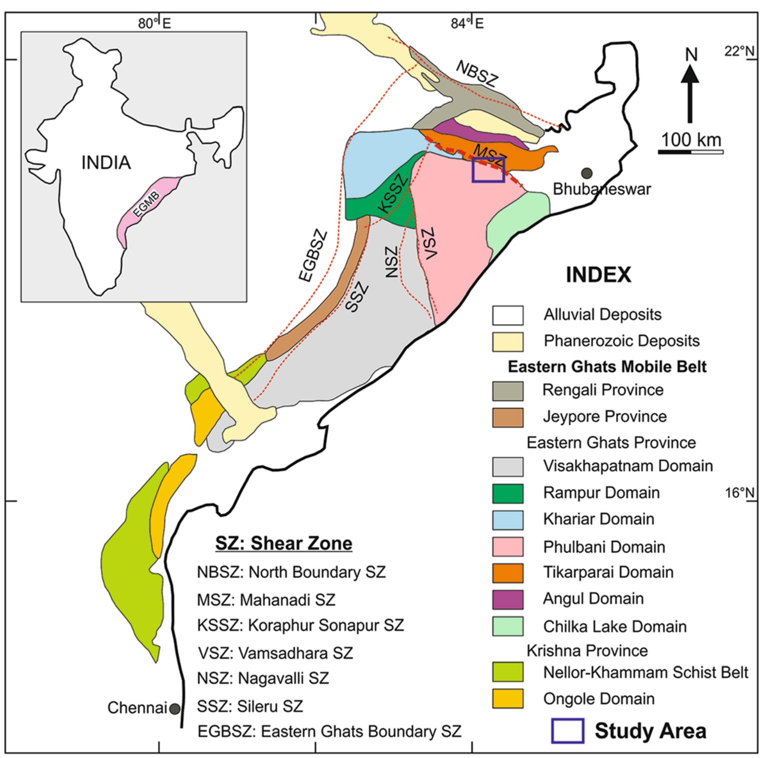

Figure 1. Map showing different domains of the Eastern Ghats Mobile Belt (EGMB) by Dobmeier and Raith (2003) and shear zones marked by Chetty and his co-workers (Chetty 2001, 2014; Chetty *et al.* 2003). Position of the Mahanadi Shear Zone (MSZ) is indicated as dashed thick red line. (Inset) Position of EGMB is shown in map of India.

and paleo-seismicity, this present study will be useful to understand the processes involved in the evolution of the MSZ.

2. Regional geology

Peninsular India is a composite of several Archaean cratons which amalgamated along the mobile belts. The NE–SW trending Proterozoic Eastern Ghats Mobile Belt (EGMB) is one such mobile belt in the eastern part of the Indian peninsula which is placed between India and East Antarctica in reconstructions of the Gondwanaland (Collins and Pisarevsky 2005; Veevers 2009, 2012; Merdith *et al.* 2017). The EGMB is dominated by metasedimentary granulites (Mg–Al granulite, calc-granulite, khondalite, and quartzite), charnockite-enderbite, mafic granulite, migmatitic quartzofeldspathic gneiss, leptynite, anorthosite and alkaline complexes (Mukhopadhyay and Basak 2009). The multiply deformed and polymetamorphosed EGMB has been described as a collage of several crustal segments having distinct geological, geochronological and structural history which are separated by linear to curvilinear lineaments and major shear zones (Chetty and Murthy 1998; Chetty 2001, 2014; Chetty *et al.* 2003; Dobmeier and Raith 2003; Nanda 2008; Mahapatro *et al.* 2009; Bose and Gupta 2018) (figure 1). Based on lithological association, metamorphic and structural evolution and isotopic characters, Dobmeier and Raith (2003) divided the EGMB into four provinces, viz., the Rengali Province (RP), Eastern Ghats Province (EGP), Jeypore Province (JP) and Krishna Province (KP) from north to south. These provinces are further subdivided into domains. The Mahanadi Shear Zone (MSZ) is one among the major shear zones separating different provinces and domains of the EGMB, which separates the southern segment of the EGMB having dominant NE–SW structural trend from the northern segment having dominant E–W trend (Mahapatro *et al.* 2009) (figure 1). The northern segment of the Eastern Ghats Province (EGP) is separated from the Rengali Province/domain by a tectonic zone known as the Mahanadi tectonic zone or rift system (Mahapatro *et al.* 2009; Chetty 2014). The MSZ and Kerajang Shear Zone (KSZ) represent southern and northern boundaries of the Mahanadi rift system respectively in the EGMB of the Indian segment (Mahapatro *et al.* 2009; Bose and Gupta 2018). The KSZ also marks the southern boundary of the Neoarchaean Rengali Province (Nash *et al.* 1996). The evolution of this tectonic zone may have bearing on the evolution of crustal domain between the Grenvillian Eastern Ghats Province and the Singhbhum Craton.

3. Mahanadi Shear Zone

The Mahanadi Shear Zone (MSZ) is ∼200 km long and 3–8 km wide WNW–ESE trending curvilinear high strain zone represented by extensive mylonite and ultramylonite along the southern shoulder of the present alignment of Mahanadi River (Mahapatro *et al.* 2009; Moharana and Ghosh 2014). The MSZ is transverse to the general NE–SW trend of EGMB, north of which the dominant structural trend shows a dextral drag and becomes parallel with the WNW shear fabric of the MSZ. The MSZ is a high-temperature ductile shear zone at the southern shoulder of the Mahanadi graben in which mylonite–ultramylonite occurs intimately associated with pseudotachylite. Mahapatro *et al.* (2009) related the MSZ with extensional tectonics with a negligible dextral strike-slip component and observed no overprinting of mylonitic fabric on pseudotachylites within MSZ. They explained the formation of pseudotachylite by brittle failure without passing through plastic deformation and suggested a two-stage development for mylonite–ultramylonite and pseudotachylite in the MSZ.

Bose and Gupta (2018) refuted the observation of Mahapatro *et al.* (2009) and inferred that the lineations in the MSZ are shallow plunging in nature. They associated these lineations with predominantly dextral strike-slip movement, related to D_3 deformation. Later, Bose *et al.* (2020) amended their inference and identified two separate shearing events (D_3 and D_4 of Bose and Gupta 2018) along the MSZ. The first was a predominantly extensional shearing event during D_3, which transposed and reoriented the earlier S_1/S_2 granulite facies fabrics, similar to the inference of Mahapatro *et al.* (2009). According to them, the sub-horizontal lineations in the MSZ represent the second shearing event during D_4. According to these workers, the extensional shearing event operated under middle amphibolite facies condition at ∼730–680 Ma and the lateral movement event operated under middle greenschist facies condition at ∼520–510 Ma in the MSZ (Bose and Gupta 2018; Bose *et al.* 2020). They suggested that the strain related to the later shearing event is localized in nature, and the strain related to this event is partitioned along narrow event linear domains north which manifested in the form of infrequent shear bands. However, these workers have not studied the pseudotachylites associated with the MSZ. In a recent study, Ghosh *et al.* (2021) included the Tikarpada domain as part of the MSZ and interpreted the MSZ as an intra-terrane transpressional zone having triclinic symmetry of deformation with simple shear along and pure shear (shortening) perpendicular to the mylonitic fabric. They suggested dextral shear sense of the dominant strike–slip component and reverse sense of the less prominent dip-slip component.

The present study is based on the work carried out in the eastern segment of MSZ between Kalatangi in the SE and Purunapani in the west extending for over 50 km in the southern bank of Mahanadi River (figure 2). This high strain zone trends WNW–ESE in the east and gradually swerves to an E–W trend in the west. The zone is about 2–3 km wide in the central part which narrows down towards east. The geology around the present study area was mapped and further demarcated the detailed lithological and structural elements by Mahapatro *et al.* (2009). The study area hosts an interbanded sequence of khondalite, quartzite and Mg–Al metapelite along with orthogneisses such as charnockite, enderbite, mafic granulite, granite gneiss and leptynite (figure 2). Khondalites comprising of garnet + sillimanite + biotite + quartz + K-feldspar ± graphite with bands of quartzite (± garnet ± sillimanite) and minor cordierite + garnet + sillimanite + K-feldspar + quartz gneiss.

Presence of two textural variants of anhydrous and hydrous quartzo-feldspathic orthogneiss, viz., charnockite–enderbite and granitoids are typical of this area. Texturally, these are either medium-grained equigranular nature or very coarse-grained with K-feldspar megacrysts. Garnet is commonly present in both variants of these rocks. Two-pyroxene mafic granulites occur as thin to thick concordant sheets within charnockites and khondalites. Local arrested development of patchy charnockite is observed in the gneissic granites and leptynites along and across the gneissic foliation. Intense ductile shearing in the MSZ has resulted in extensive mylonitization of these litho-units and rotation of the regional foliation. The shear zone is demarcated from the rocks exposed in its south and north by the presence of mylonites and ultramylonites.

3.1 *Pseudotachylites in MSZ*

Pseudotachylites occur as aphanitic dark coloured veins and bands distributed throughout the MSZ, which can be easily discernable among other

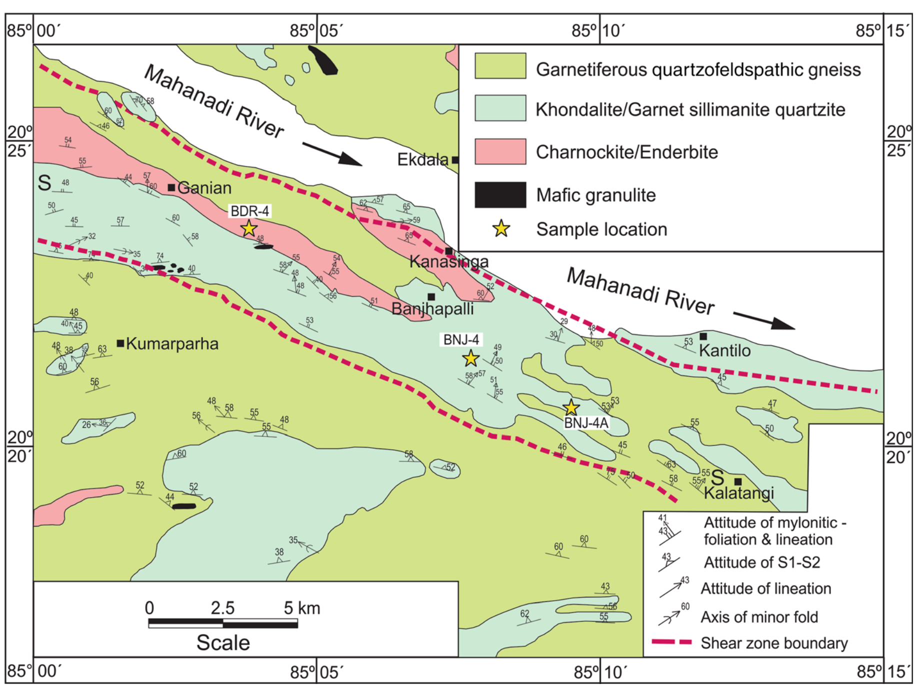

Figure 2. Generalized geological map of the Mahanadi Shear Zone (modified after Mahapatro *et al.* 2009).

variety of rocks in the study area (figure 3a–f). Their texture, form and nature (injection veins, or other cross-cutting relationships) make them easy to identify in outcrops. The veins vary in thickness from a few millimeter to tens of centimeter. Pseudotachylite vein of tabular band (figure 3a) to variable thickness (figure 3b) mostly disposed subparallel to foliation in quartzofeldspathic mylonite. The mylonitic foliation in the host rock is generally crosscut by pseudotachylite veins, and rarely disposed along the foliation (figure 3d). Individual pseudotachylite veins, particularly in the quartzofeldspathic mylonites, can be traced for up to a few meters along the length in those places where exposures are available. The host rock is locally brecciated disrupting mylonitic foliation whereby thick and patchy pseudotachylite constitutes the matrix surrounding the clasts (figures 3c, 4a). Interconnected network of pseudotachylites in highly cataclastic granite mylonite and fault breccia show network of relatively thick and patchy pseudotachylite veins containing different sizes of clasts (figure 3e, f). The clasts in these parts are subrounded to subangular assorted fragments of mylonite, ultramylonite found embedded in pseudotachylite matrix similar to 'Type C (sinuous network of pseudotachylite veins)' described by Lund and Austrheim (2003) and 'Pseudotachylite zone' by Allen (2005). In such case, both generation veins (major failure surfaces of comminution/ melt generation) and injection veins (failure planes at an angle to movement direction) swell to form bulbous pockets of melt. These zones are abruptly bounded by wall rocks (figure 3e, f). The planar (gneissic and mylonitic) fabrics in these clasts make low to high angles with that in the neighbouring clasts (figure 3c, e, f), thereby suggesting rotation of clasts. In all these outcrops, pseudotachylite appears to have been formed by rupture of intact country rocks and post-dates to shearing.

Pseudotachylites under microscope appear grey to dark brown under plane-polarized light and patchy isotropic (i.e., glassy) under crossed polars (figure 4). These appear as dark thin bands either as parallel or sub-parallel to mylonitic foliation (C-planes), or cross-cut at a high angle to it (figure 4a, b). In khondalite, grain-scale ductile and brittle deformation of minerals such as quartz, feldspar, sillimanite is clearly discernible adjacent to the pseudotachylite veinlets (figure 4a). In high-resolution back-scattered electron (BSE) images, pseudotachylite generation and injection veins appear traversing into host khondalite mylonite (figure 5a, b). Further, pseudotachylites comprise of rounded to sub-rounded clasts of host rock/ minerals in an extremely fine-grained matrix (grain size on the order of a few microns) with crude flow structure (figure 5a, d). Embayed margins of the clasts are also occasionally noticed. Rare presence of dendritic skeletal microlites and quenched melts microstructures are also identified (see Mahapatro *et al.* 2009) indicating insignificant melt involvement.

4. Methodology of clasts size analysis

Statistical approaches involving grain-size distribution of fragments within pseudotachylite veins have been employed to quantitatively examine and know the mechanism of formation of pseudotachylites, their relationship with host shear zone structures including encompassing host rocks and mode of evolution (Shimamoto and Nagahama 1992; Tsutsumi 1999; Ray 1999, 2004). In view of varying interpretations regarding the formation of pseudotachylites by different researchers (discussed earlier), size analysis of pseudotachylite clasts has been carried out to evaluate the process of formation of pseudotachylites, and thus comment on the evolution of the MSZ. Pseudotachylites usually consist of clasts of different size in a fine-grained matrix. Grain size analysis of fragments is generally based on microscopic observations. The nature of pseudotachylite matrix and its optical contrast with respect to the clasts under polarized microscope enable trouble-free recognition. The clasts stand out prominently in the pseudotachylite matrix (Hetzel *et al.* 1996). The measurement of clast size *vs.* frequency distribution is carried out in thin sections. The studied thin sections are divided into grids of 1 mm × 1 mm using transparent sheet similar to the process described by Behera *et al.* (2017).

Pseudotachylites may form during brittle faulting and ductile shearing and remain as veins in close association with the interface of wall rocks (Ray 2004). Reduction of grain-size is a ubiquitous phenomenon within such fault rocks associated with both brittle and ductile fault/shear zones. A linear relationship between grain size and the cumulative number of fragments has been documented in pseudotachylites (Okamoto and Kitamura 1990, 1996). Studies by Shimamoto and

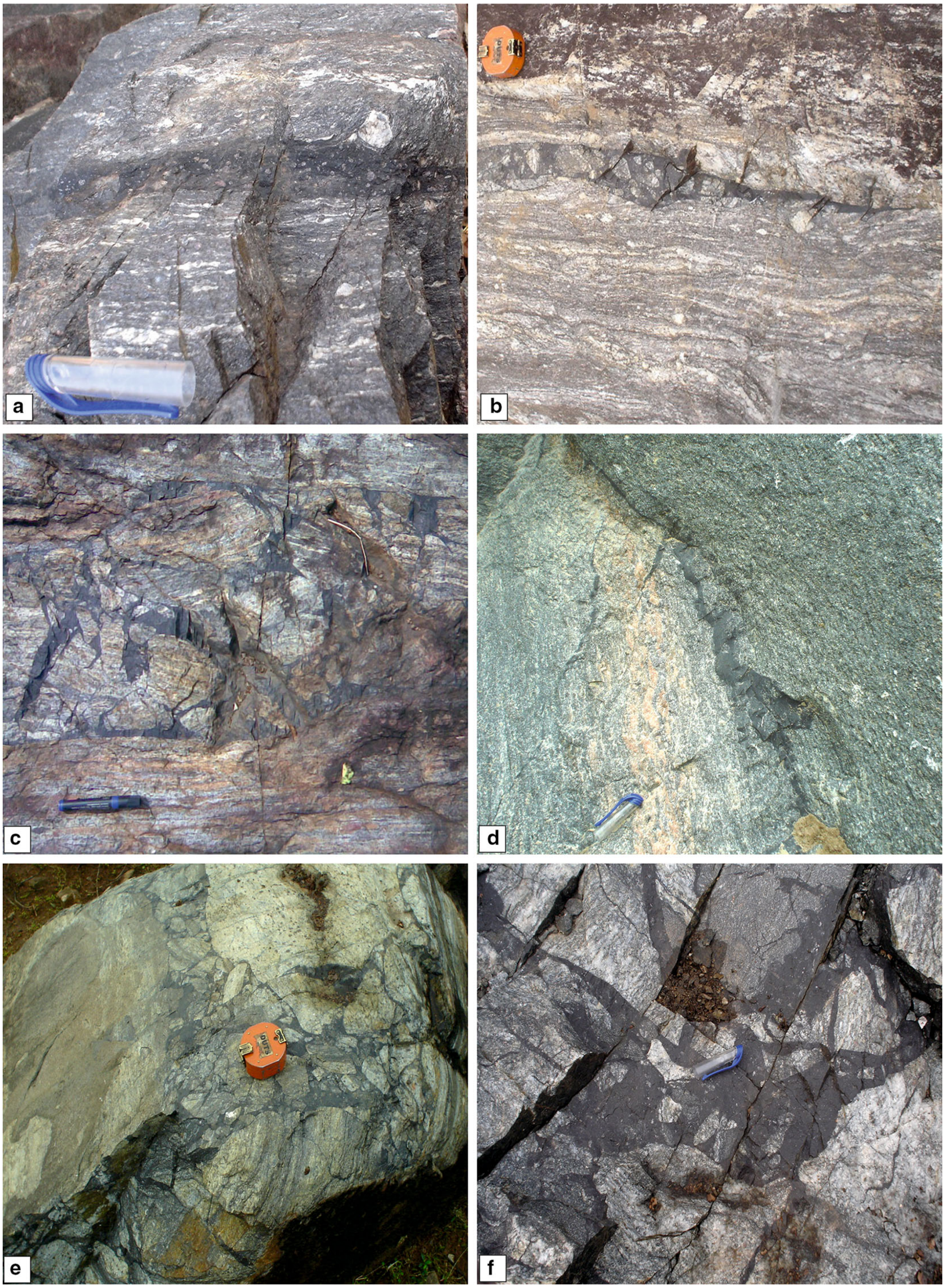

Figure 3. Field relationship of pseudotachylite and host mylonite. (**a**) Tabular band of pseudotachylite disposed subparallel to foliation in quartzofeldspathic mylonite, (**b**) Pseudotachylite vein of variable thickness disposed subparallel to foliation in quartzofeldspathic mylonite, (**c**) Pseudotachylite breccia disrupting mylonitic foliation. Note the relative rotation of clasts, their generally angular shape and the wide range of clast sizes, (**d**) Pseudotachylite veins disposed subparallel to fabric in the quartzofeldspathic gneiss, (**e**) Interconnected network of pseudotachylites in highly cataclastic granite mylonite, and (**f**) fault breccia showing network of relatively thick and patchy pseudotachylite veins containing different sizes of clasts.

Nagahama (1992) indicated that the sizes of fragments show a fractal distribution on a grain size–frequency distribution diagram for certain ranges of grain size, and they proposed a basic equation (Power Law relationship) for the fractal analysis of fragments as given below:

$$N = cu^{-D}, \quad (1)$$

or

$$\log N = \log c - D \log u, \qquad (2)$$

where 'N' is the cumulative number of fragments with sizes greater than 'u'. The exponent 'D' represents the fractal dimension, i.e., the slope of the straight-line part of the curve, and 'c' is proportionality constant that depends on the number of measurements. Plotting of clasts size (u) *vs.* cumulative number of clasts (N) (i.e., frequency) in log–log coordinates as X- and Y-axes respectively yield straight-line graphs. The value of 'D' can be obtained by determining the slope of a least-squares fitted straight line on the diagram. However, Ray (1999, 2004) recognised a slight departure from the Power-law relationship (modified Power Law distribution), similar to those reported by Tsutsumi (1999) for experimentally generated pseudotachylite. According to them, instead of a straight-line the trend gently curves towards finer grain sizes in the log–log plot of fragment size (u) *vs.* cumulative frequency (N). The subsequent processes may modify the Power-law pattern, but cannot destroy it (Ray 2004). The data inputs for size (area in μm^2) and number of clasts (N) are used to construct log–log graphs, based on Power Law size distribution.

5. Results

The pseudotachylites within the MSZ comprise of fragments of surrounding rocks which include a wide range of size distribution. The photomicrographs of pseudotachylite samples have been converted to binary images to eliminate the background effect, and used for statistical analysis of clasts (figure 6). All images have been processed through imageJ software where the minimum threshold size is 10 micron square and the maximum is 100,000 micron square. In order to avoid the repetition in measurement, we have discarded those particles which are present at the edge of the frame and counted each particle. The circularity of particles is taken from 0 to 1 and calibrated with the actual scale of the photomicrograph.

Three samples of pseudotachylites occurring in charnockite ((BDR–4) and khondalite (BNJ–4 and BNJ–4a) from different localities of the MSZ (figure 2) are analysed and plotted taking clasts size (u) and cumulative number of clasts (N) in logarithmic scales on X- and Y-axes respectively (figure 7a, b, c). The points on 'u' *vs.* 'N' in log–log graphs for all these locations are largely distributed along the best fit straight line and follow the Power Law of size-frequency distribution pattern without any fall-off of the points for lower values of clast size (u). The linearity in log–log graphs suggests involvement of 'self-similarity pattern' in the process of formation and fragmentation of pseudotachylites in the MSZ. Slope of the best fit line or fractal dimension (D) for the studied samples is determined from the auto-generated equation using MS excel (figure 7a, b, c), which varies from 0.51 to 0.69 (tables 1, 2, 3). The close similarity in graphs and low variation of D values observed in all three studied samples, suggest that pseudotachylites in various rock types at different

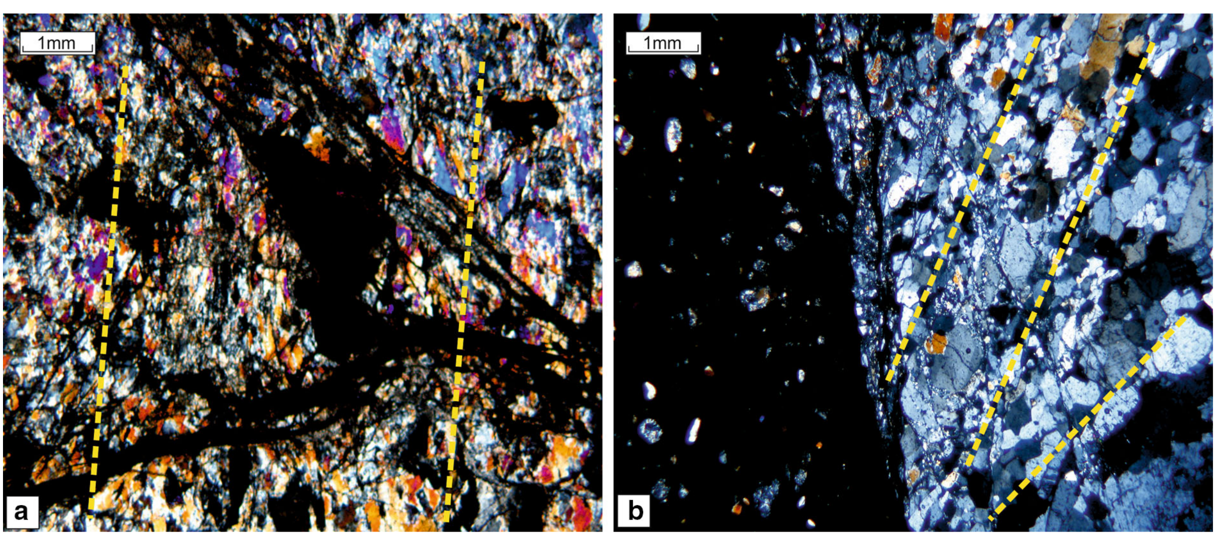

Figure 4. Photomicrographs of pseudotachylites (**a**) network of pseudotachylite veins disposed sub-parallel to as well as cutting across mylonitic foliation and (**b**) pseudotachylites cross-cutting foliation in the host rock. Note: dotted yellow lines indicate mylonitic foliation.

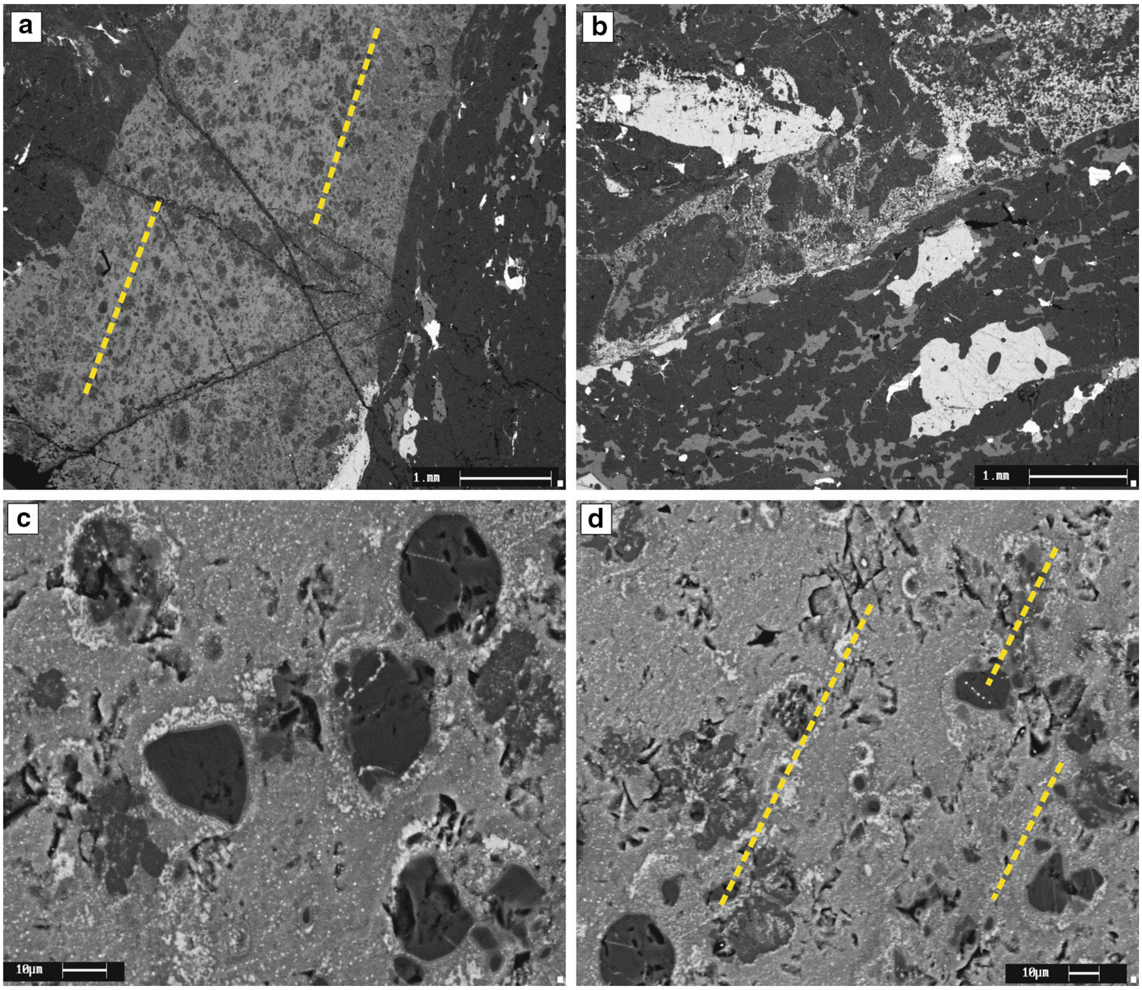

Figure 5. Back Scattered Electron (BSE) images of pseudotachylites of MSZ. (**a**) Pseudotachylite injection veins (in central part) traversing parallel into host khondalite mylonite from Purunapani area, (**b**) khondalites mylonite with pseudotachylite veins disposed parallel to mylonitic foliation defined by stretched and ribbonised quartz (darker), feldspar (lighter) and elongated garnet (bright grains) porphyroclasts from Banjhapalli area, (**c** and **d**) presence of thin rims of spherulites-microlites around rounded to sub-rounded lithic clasts and dendritic skeletal microlites in the matrix supported pseudotachylites in khondalite from Purunapani area. Note: dotted yellow lines indicate crude flow structure.

localities in the MSZ developed during a single event (see Ray 2004; Behera *et al.* 2017).

6. Discussion

The MSZ is a ductile shear zone where pseudotachylite occurs intimately associated with mylonite-ultramylonite. Coexistence of pseudotachylites and mylonites have also been reported from many other terrains and their mutually-overprinting relationships are studied by many researchers (Sibson 1980; Passchier 1982, 1984; Takagi *et al.* 2000; Lin *et al.* 2003, 2005; Ueda *et al.* 2008; Price *et al.* 2012; Kirkpatrick and Rowe 2013). Pseudotachylites forming under the same conditions as mylonites, retain textural details such as primary structures, mineral recrystallization, reaction between grains and viscous deformation while passing from undeformed to deformed state (Price *et al.* 2012 and references therein).

The size distribution of fragments within pseudotachylite is an indicator of the mechanisms associated with its formation (Shimamoto and Nagahama 1992; Lin 1994, 2008; Ray 1999, 2004; Tsutsumi 1999). The Power-law relationship has been widely used as a quantified index of frictional melting to understand the process of formation of the pseudotachylite fragments (e.g., Shimamoto and Nagahama 1992; Ray 1999, 2004; Tsutsumi 1999). The modified Power law is treated as a proxy for characterization of cataclastic deformation and involvement of high heat flow during the formation of pseudotachylites (Ray 1999, 2004).

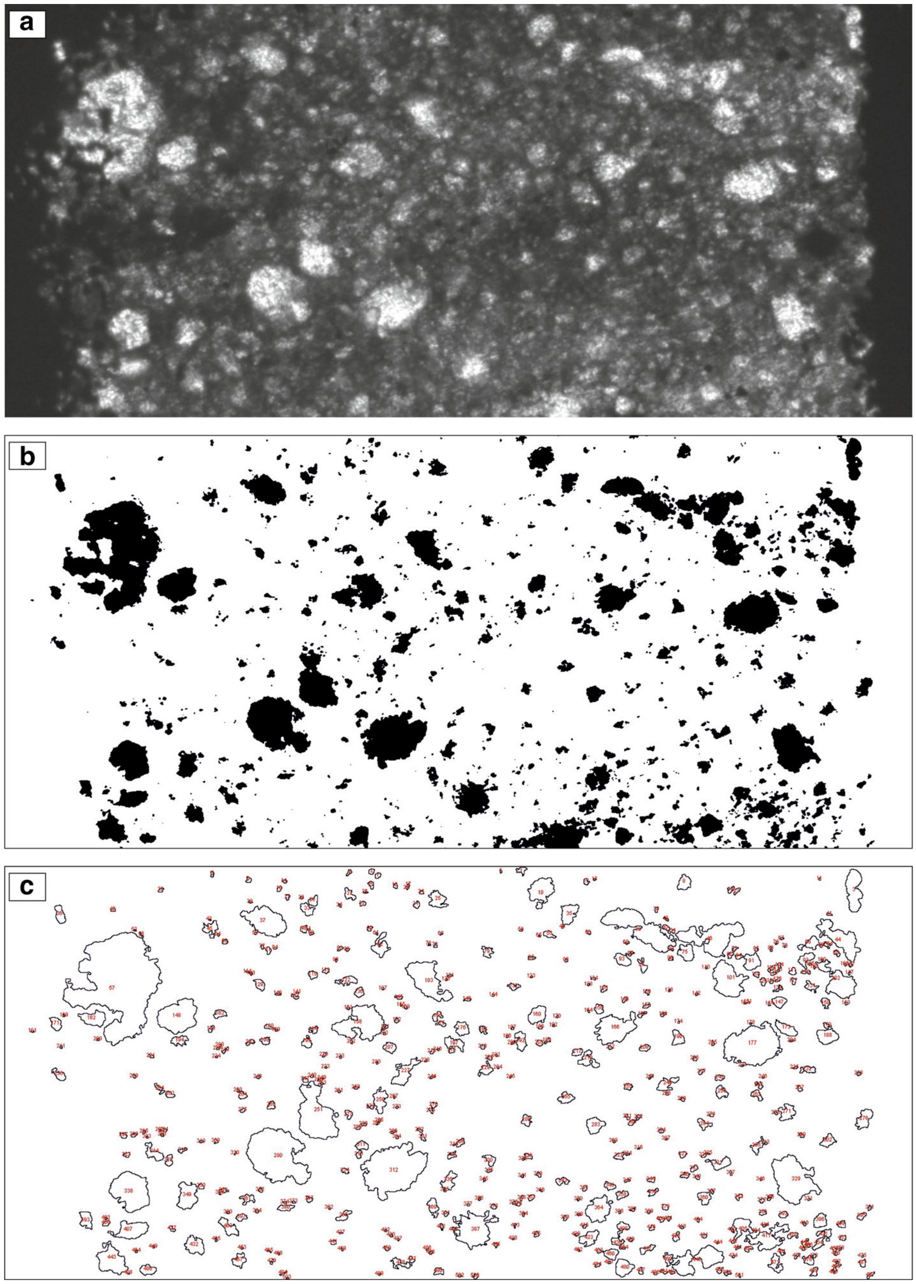

Figure 6. (**a**) Photomicrograph of pseudotachylite, brighter clasts and grey matrix, (**b**) same photo processed to binary image after background correction through 'imageJ' software to measure clast size, and (**c**) outline of individual clast used in size measurement for size-frequency analysis.

It has been widely considered that bending of the linear curve towards finer grain-size indicates formation of pseudotachylites by subsequent processes of transformation and involvement of comminution-induced melting of the host rock (Shimamoto and Nagahama 1992; Ray 1999; Tsutsumi 1999). In this study, the *u vs. N* graphs of the MSZ pseudotachylites show very good correlation with the best fit line without any fallout and thereby follow the 'Power Law' without any modification (figure 7a, b, c). From equation (1), the fractal dimension (D) represents the slope of the best fit line in *u vs. N* graph and for this present study D varies between 0.51 and 0.69 (tables 1, 2, 3). Generally, D value varies from 0.5 to 2.9991 and is proportional to the strain involved (Marone and Scholz 1989; Ray 1999; Tsutsumi 1999; Glazner and Mills 2012). Lower D value suggests a wide range of size distribution. From graphs of this study, it is clearly evident that occurrences of finer clasts ($<250\ \mu m^2$) are also proportionate with coarse

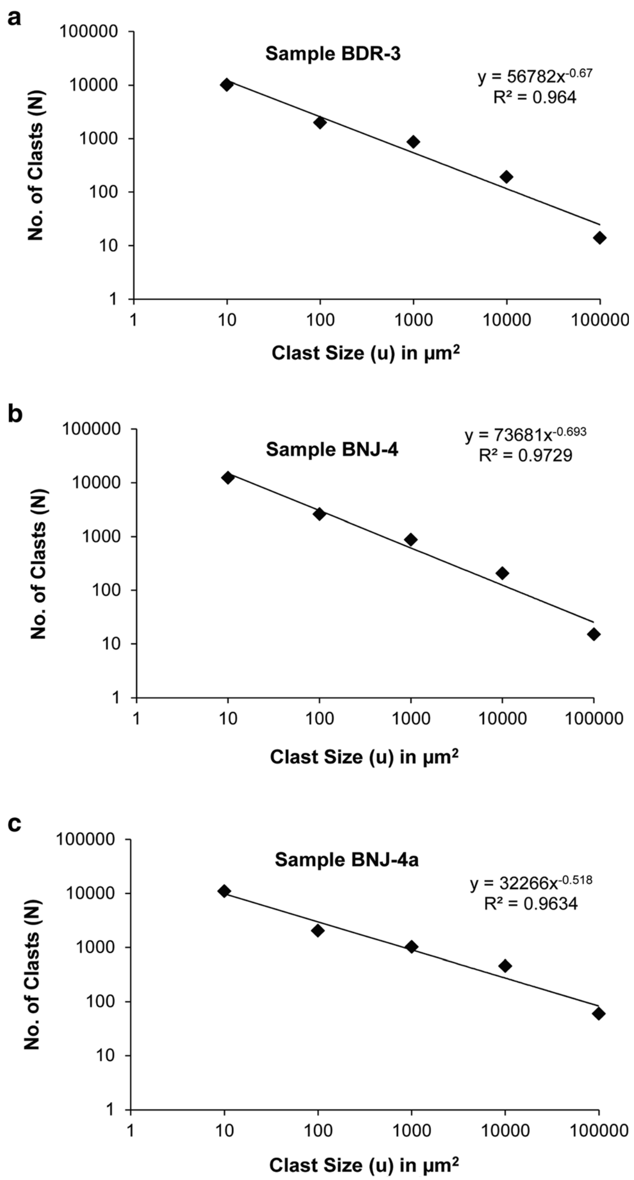

Figure 7. Log–log plots of fragment sizes (u, in terms of area) against cumulative frequency (N), of pseudotachylite exposed in different parts of the Mahanadi Shear Zone (**a**) from Budapara, (**b**) and (**c**) from Banjhapalli area.

Table 1. *Frequency of the clasts with areas. Sample BDR-4, charnockite (photomicrographs taken @ 10× optical zoom).*

Area (μm^2)	Frequency	
10	10,096	
100	1992	
1000	869	
10,000	191	
100,000	14	
Total clasts	13,162	$D = 0.67$

Table 2. *Frequency of the clasts with areas. Sample BNJ-4, khondalite (photomicrographs taken @ 10× optical zoom).*

Area (μm^2)	Frequency	
10	12,342	
100	2601	
1000	876	
10,000	206	
100,000	15	
Total clasts	16,040	$D = 0.69$

Table 3. *Frequency of the clasts with areas. Sample BNJ-4a, khondalite (photomicrographs taken @ 10× optical zoom).*

Area (μm^2)	Frequency	
10	10,869	
100	2021	
1000	1010	
10,000	452	
100,000	59	
Total clasts	14,411	$D = 0.51$

grains and coherency of low D values is also maintained. The 'Power Law' pattern, low D values and involvement of large range of size distribution of fragments in the MSZ pseudotachylites indicate high strain rate during brittle deformation and can be attributed to a combination of crushing and melting processes (Shimamoto and Nagahama 1992). These also point towards a single event of formation in a self-similarity mechanism and probably not affected by subsequent deformations (Ray 1999, 2004; Behera *et al.* 2017). The field and petrographic observations also corroborate these inferences.

The mobile belts bordering ancient cratons were locale for magmatism, metamorphism and intense deformation, similar to present-day plate margins. The terrane boundary shear zones, as well as intra-terrane high strain zones within mobile belts, are sites of multiple reactivation and foci of paleoseismicity. The MSZ is one such high-strain zone that evolved in multiple episodes of brittle and ductile deformation, where pseudotachylites and mylonite-ultramylonites coexist in granulite grade rocks such as khondalite and charnockite (Nash *et al.* 1996; Mahapatro *et al.* 2009). Field and petrographic studies suggest that the MSZ is a high-temperature ductile shear zone. The ductile shearing in the MSZ operated under high-temperature conditions as observed from the presence of sigmoidal garnets and sillimanite fish (Mahapatro *et al.* 2009). However, features such as sigmoidal/asymmetric nature of clasts, and overprinting of mylonitic fabric are observed in the pseudotachylites of the MSZ irrespective of the scale of observation (see Price *et al.* 2012). The pseudotachylites of the MSZ often cut across the mylonitic fabric, and most of these veins and zones do not follow the orientation as the mylonitic fabric (see Mahapatro *et al.* 2009). These pseudotachylites occasionally exhibit crude flow structures (figure 5a, d), rims around clasts (figure 5c, d). In addition, there is variation in orientation of fabrics in the clasts occurring together within pseudotachylite zones. These features clearly indicate that the mylonitic fabric predates brittle deformation, and the pseudotachylites have not suffered any subsequent deformation after their formation. Therefore, the brittle deformation related to pseudotachylite formation is subsequent to ductile shearing in the MSZ. Mahapatro *et al.* (2009) also inferred that the MSZ pseudotachylites have formed under a brittle regime at later stage of reactivation of the shear zone and occurred at a shallow crustal depth without passing into plastic deformation. It may be emphasized that the Mahanadi Tectonic Zone extends from the MSZ in the south up to the southern boundary of the Rengali Province, i.e., up to the Kerajang Fault/Shear Zone in the north. The Gondwana sediments are deposited in the northern part of this tectonic zone. The pseudotachylites in the tectonic zone yielded Pan-African ($\sim$515 Ma) signature (Lisker and Fachmann 2001). Based on fission-track analyses on zircons, they suggested two-stage development of the Mahanadi Basin as an asymmetrical half-graben by rifting during the Permo-Carboniferous and the Middle Triassic. Therefore, the pseudotachylites of the MSZ can be attributed to a deformation history independent of ductile shearing related to reactivation at a later stage, possibly during Pan-African time.

7. Conclusion

The MSZ is a high-temperature ductile shear zone at the southern shoulder of the Mahanadi Tectonic Zone. The MSZ is characterized by brittle–ductile deformation and coexistence of pseudotachylite and mylonite–ultramylonite. The present study suggests two-stage evolution of the MSZ, i.e., early development of mylonite–ultramylonite by ductile deformation at deeper level followed by pseudotachylite development at later stage by brittle deformation under high strain rate at a shallower level. The brittle deformation in the MSZ is related to reactivation at a later stage which overprinted the ductile deformation.

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Author statement

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