



Pseudotachylyte-Induced Weakness of Plate-Boundary Fault: Insight from the Indus-Tsangpo Suture between India and Asia

XU Zhiqin^{1,*}, JI Shaocheng^{2,*} and ZHOU Xin³

¹ School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China

² Département des Génies Civil, Géologique et des Mines, École Polytechnique de Montréal, Montréal, Québec, H3C 3A7, Canada

³ Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037

Abstract: Although the Indus-Tsangpo Suture (ITS) is the most spectacular thrust system of continent-continent collision in the world, fundamental questions about its strength evolution and deformation behavior transition remain unanswered. Here we reported, for the first time, frictional melting-induced pseudotachylytes in the intensively deformed felsic rocks along the ITS zone in southern Tibet. This study reveals that pseudotachylytes induced profound weakness of the boundary fault between Indian and Asian plates. The intrinsically low strength of the foliated microlites crystallized from frictional melt or glass (i.e., pseudotachylyte) at seismogenic depths compared with the surrounding coarse-grained quartzofeldspathic rocks in the brittle and semi-brittle regime is sufficient to explain the localization of shear strain, the development of ductile shear zones embedded in strong wall rocks, and the transition from the strong to weak fault behaviors without invoking the presence of high fluid pressure or low friction coefficient metasomatic materials (e.g., smectite or lizardite) within the faults.

Key words: pseudotachylyte, mylonite, fault strength, strain localization, Indus-Tsangpo suture, Tibet

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1 Introduction

The deformation behavior of plate bounding faults changes with depth: brittle behavior such as frictional sliding and dilatational fracturing is prevailing in the upper crust while ductile behavior is dominant in the mid-to-lower crust where temperature is high enough to promote plastic micro-mechanisms such as dislocation creep and/or diffusion creep (Scholz, 2002; Ji and Xia, 2002). Both frictional sliding and fracturing processes are sensitive to effective pressure, yielding a linear increase in rock strength with increasing depth (Byerlee, 1978). However, the ductile behavior, which is sensitive to temperature, leads to a non-linear decrease in rock strength with increasing depth. As a result, a peak in rock strength occurs in the brittle-ductile transition zone, which usually ranges over a depth interval of 12–20 km depending on the regional geothermal structure and lithology, and is believed to coincide with the seismic to aseismic transition in the continental crust (Scholz, 2002).

Despite 30 years of research, whether fault zones (e.g., the San Andreas Fault) are stronger or weaker than expected from laboratory determined Byerlee's law with friction coefficients in the range 0.6–1.0 remain controversial (Scholz, 2000; Townend and Zoback, 2000;

Zoback et al., 2000; Collettini et al., 2009). The crust-averaging shear stress on the San Andreas Fault was estimated to be in the range of 100–160 MPa although the regional geothermal gradient is as high as 22–26 °C/km (Scholz, 2000; Terakawa and Matsu'ura, 2009). Pervasive fluid influx, which alters the load-bearing mineral phases to produce fine-grained aggregates of weak, platy minerals (e.g., smectite clays below 150 °C, and illite-smectite mixtures between 150–260 °C), may explain the local shear stress becoming lower than 20 MPa, equivalent to a coefficient of friction of 0.10–0.15 (Carpenter et al., 2011; Lockner et al., 2011), in the creep segments. However, the fluid migration and resultant retrograde reaction and dissolution-precipitation deformation are efficient only when rocks within the fault zone have been crushed by early earthquakes to form porous, fine-grained aggregates (e.g., gouge and cataclasite). In a newly formed fault zone, the dry, intact rocks containing little hydrated and altered products should form locked segments and produce great earthquakes. Even along a relatively mature fault zone such as the San Andreas fault which has been active since ~20 Ma ago, all segments are not equally weak.

Pseudotachylyte, which is a quenched melt with minor inclusions of refractory mineral or wall rock clasts (Fig. 1), was generated by high-velocity (m/s) frictional slip along the strong faults. The presence of pseudotachylyte is regarded as an indicator of brittle and/or semi-brittle

* Corresponding author. E-mail: xzq@nju.edu.cn, sjj@polymtl.ca

behavior and thus ancient earthquake activity of fault zones (Magloughlin and Spray, 1992; Lin, 2008), and provides indirect evidence for the high strength of the fault. Plate boundaries such as oceanic subduction zones and continental collision belts are characterized by large earthquakes that contribute more than 95 % of the total global moment release (Scholz, 2002). However, more than 95% pseudotachylytes reported in the literature so far occur within exhumed intraplate fault zones (e.g., Lin, 2008; Rowe et al., 2005). Although most of the modern thrust faults related to the collision between India and Asia are extremely seismogenic, direct evidence of paleoseismicity in the exhumed fault rocks are still lacking. Furthermore, the majority of the pseudotachylytes documented previously in the literature have a characteristic vein-like morphology, forming along sliding surfaces with space-filling injections from rip-outs (Fig. 1). The pseudotachylyte veins extensively display cross-cutting relationships with the early ductility-induced foliation and have been rarely re-deformed (Fig. 1), indicating that the frictional melting occurred at the very late stage of fault rock exhumation rather than in the main period of large deformation. Here we report field and microstructural observations of pseudotachylytes within the intensively deformed rocks along the Great Counter Thrust (GCT) within the Indus-Tsangpo Suture (ITS) zone in southern Tibet. The majority of the pseudotachylites were deformed plastically after they formed. This study

reveals that pseudotachylytes induced efficiently weakness of the plate boundary thrust fault between India and Asia and were the responsible to the transition of the strong to weak fault behaviors.

2 Geological Setting

The ITS is one of the most fascinating regions in the Himalaya and the Tibetan plateau because it resulted from the continent-continent collision between India and Asia starting about 50 Ma (Yin et al., 2006). The north side of the ITS is the Gandese magmatic arc which is dominated by the Cretaceous-lower Tertiary granites (Fig. 2). The rocks of the ITS generally consist of an ophiolite mélange composed of Tethys Triassic flysch, ophiolite (i.e., serpentized harzburgite and dunite), volcanic basalt and dacite (49–65 Ma, Liang et al., 2010), and minor radiolarian chert. In the study area, the ultramafic complex was thrust to north directly on the conglomerates (i.e., the foreland molasses) which are the Oligocene (~30 Ma) or earlier continental clastic sediments (Fig. 3). The south-dipping, high-angle (>50°), reverse fault between the ophiolite and the conglomerate within the ITS zone is referred as the Great Counter Thrust (GCT, Yin et al., 2006; Xu et al., 2015). The GCT has been dated to be active at 9–20 Ma in the west Himalaya (<81°E) and 9–25 Ma in the east Himalaya (>89°E, Ratschbacher et al., 1994; Quidelleur et al., 1997; Harrison et al., 2000). In the

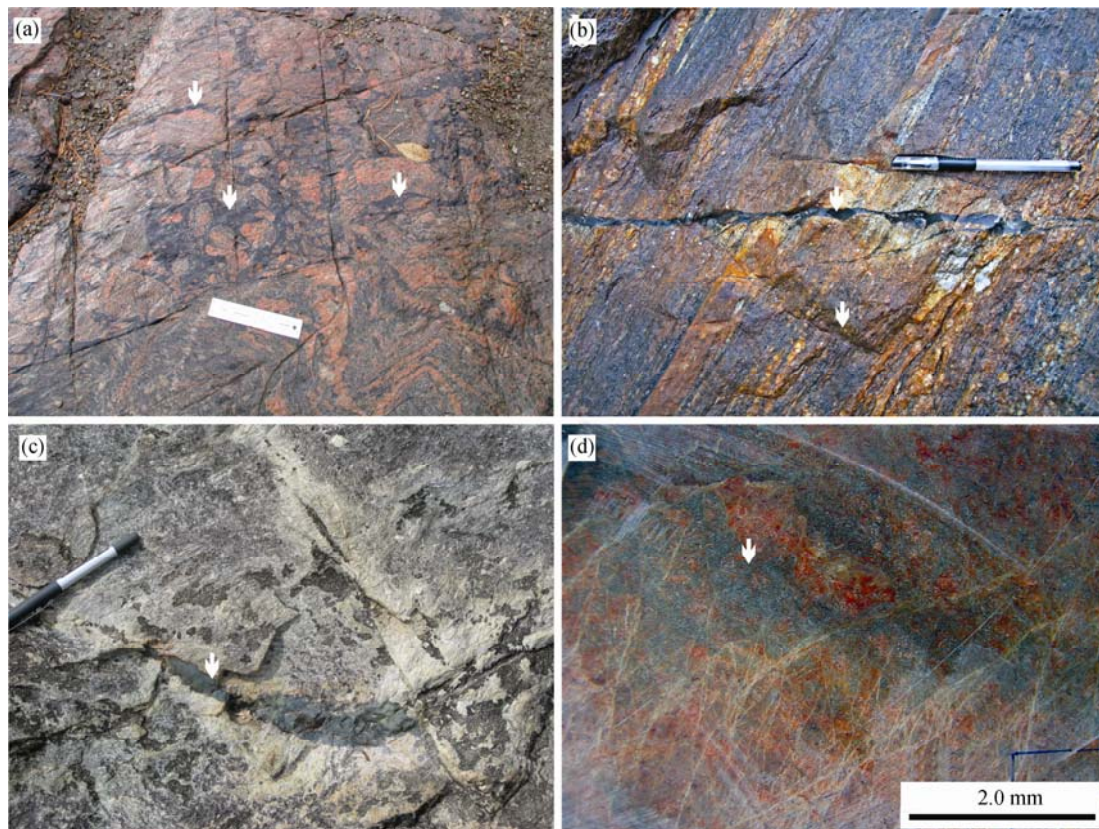


Fig. 1. Field photographs showing pseudotachylyte veins (pointed by arrow) in granitic (a, b, d) and granodioritic gneisses (c).

(a) Bellefeuille fault, Grenville Province, Quebec, Canada. (b) Gaoligong Fault Zone at Weidu Bridge, Fugong County, Yunnan, China. (c) Yunkai Mountains at Baishizhen, Xinyi City, Guangdong, China. (d) Core from the main hole of the Chinese Continental Scientific Drill Project, Donghai, Jiangsu, China.

east Himalaya, the deformation zone associated with the GCT, which extends eastward ~250 km from Zedong, through Luobusha, Kangjinla, Yubulang, and Jiacha, to Langxian (Fig. 2), is 1.0–1.5 km wide. In the south, the deformed Triassic flysch sequence is thrust over the ophiolite complex (Fig. 2).

The granitic conglomerate formation in the study areas (Fig. 2c), which was deposited non-conformably on the Gangdese granitic batholiths, can be divided into two units: the undeformed lower unit (LF1) with an average thickness of ~190 m, and the deformed upper units (LF2) with a mean thickness of ~300 m (Figs. 2c and 4a). Provenance analysis suggests that the conglomerate-forming materials were transported southward from the

Gangdese magmatic arc in the north. The gravels display an extremely large variation in size from a few centimeters to metres, indicating that the sedimentation was very rapid by landslide or subaerial deposits. Microstructural observations show no shape preferred orientation of feldspar, quartz or mica is visible within the gravels from the undeformed lower unit (LF1, Fig. 5a, b), suggesting that the gravels have not experienced significant plastic deformation either before or after the sedimentation of the conglomerates. Subgrain boundaries (Fig. 5b), which are occasionally observed in quartz crystals of the granitic gravels, indicated some weak subsolidus deformation taken place during the emplacement of the Gangdese granites (Blumenfeld et al., 1986).

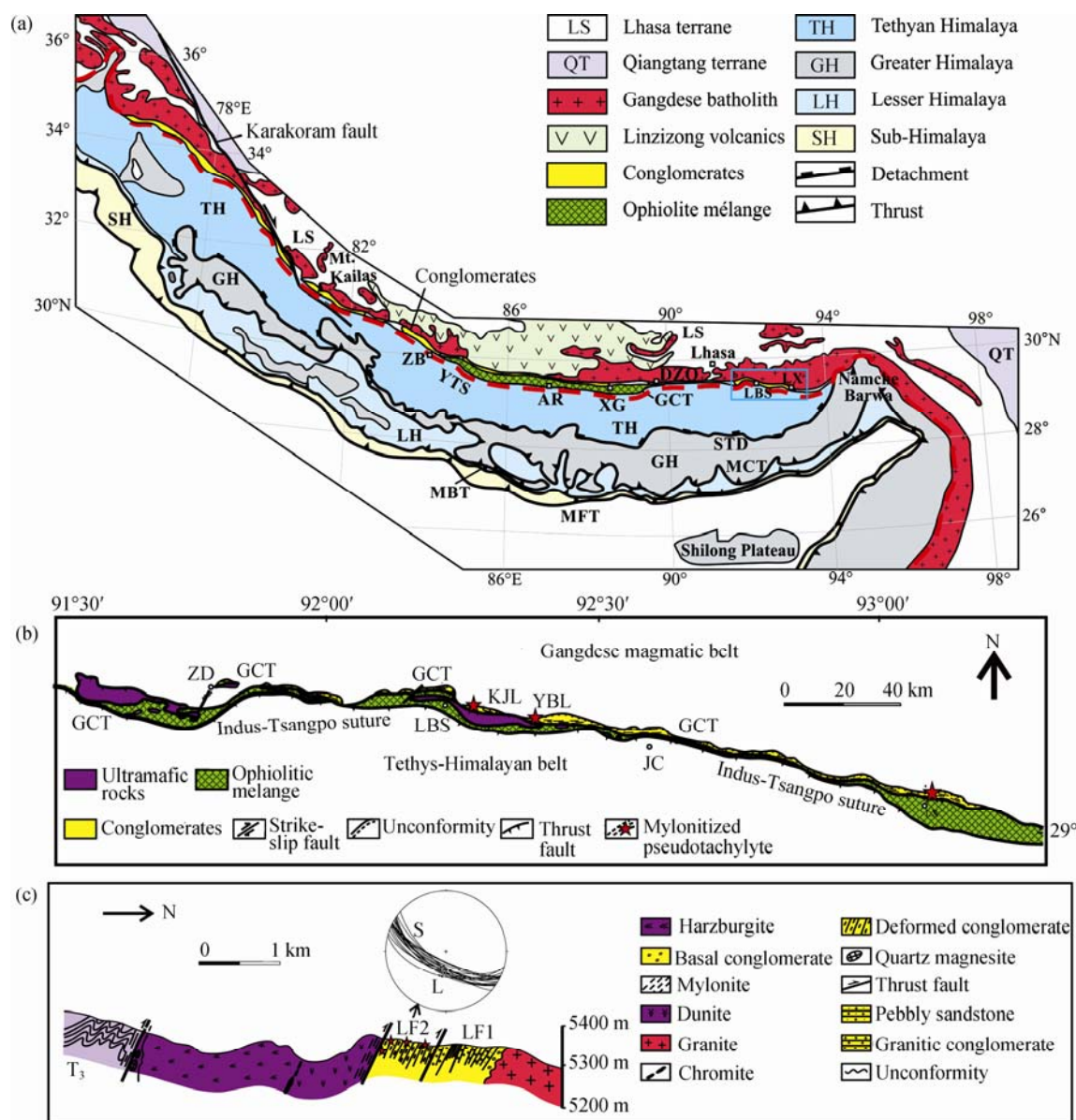


Fig. 2. Tectonic maps (a and b) and geologic cross sections (c) illustrating the Great Counter Thrust (GCT) fault zone within the Indus-Tsangpo suture (ITS) zone in the Tibetan Plateau.

Lower hemisphere projections of mylonitic foliation and stretching lineation measured in the Kangjinla Mount are given in (c). The GCT fault zone lies between the ophiolite complex in the south and the Gangdese granite in the north. MBT: main boundary thrust; MFT: main frontal thrust; MCT: main central thrust; STD: South Tibet detachment; ZB: Zhongba; ZD: Zedong; XG: Xigaze; DZQ: Dazhuqu; KJL: Kangjinla; YBL: Yubulang; LBS: Luobusha; LX: Langxian; JC: Jiacha.

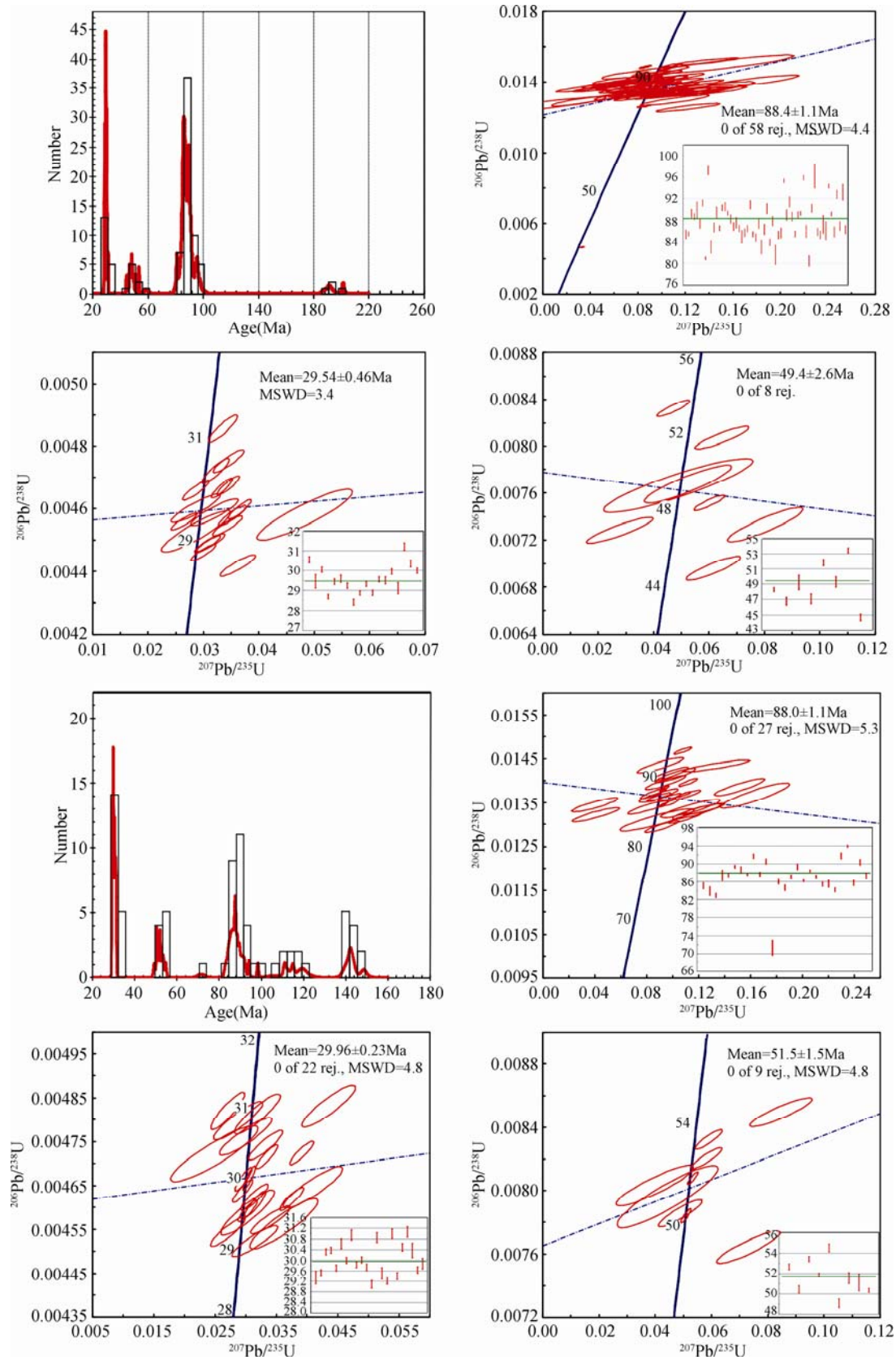


Fig. 3. U-Pb age histograms and U-Pb concordia diagrams of detrital zircons from the deformed conglomerates (Luobusha Formation) within the Indus-Tsangpo suture zone in South Tibet. Error ellipses are shown for 1 σ level of uncertainty using LA-MC-ICP-MS analyses. Samples from Kangjinla Mountain (a) and Yubulang area (b).

Pseudotachylyte veins, highly mylonitized pseudotachylyte bands and foliated host rocks coexist in LF2 (Fig. 4). The gravels, which were initially rounded to subangular in shape in LF1, have been flattened and elongated in the ductile shear zone (LF2) where the early pseudotachylytes have been deformed plastically and converted into mylonites and ultramylonites (Fig. 4). The ductile foliation defined by the flattened pebbles and the alignment of constituent minerals is dipping deeply to south while the stretching lineation is transversely oriented (Fig. 4a, c).

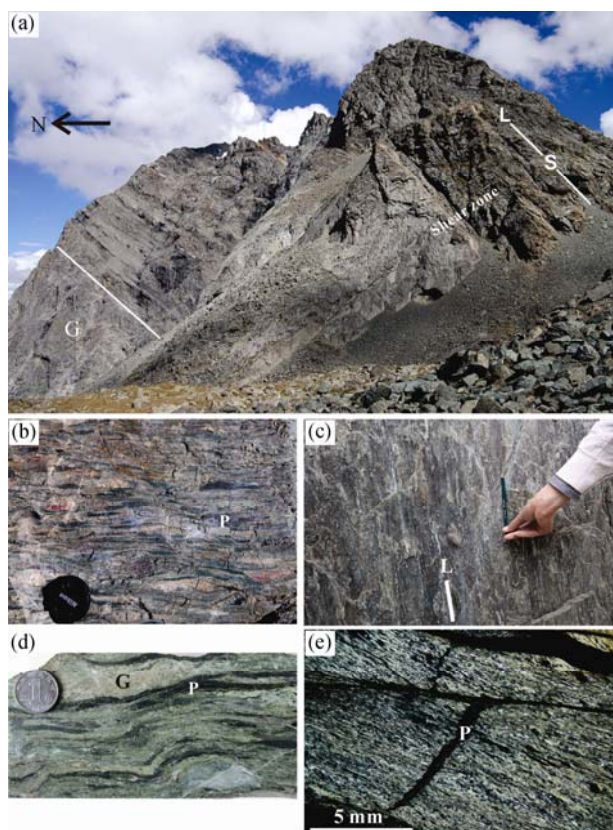


Fig. 4. The Great Counter Thrust (GCT) fault zone is characterized by strongly deformed conglomerates in which various generations of pseudotachylyte veins have been converted to mylonite and ultramylonite bands with well-developed foliation (S) dipping deeply to south and stretching lineation (L) oriented transversely (c). G: granite; P: pseudotachylyte.

Undeformed pseudotachylyte veins, which formed presumably during the latest stage, overprint post-pseudotachylyte mylonitization (Fig. 4e).

3 Tectonic Deformation

The rocks in the GCT have experienced intensive ductile formation, developing pronounced foliation and stretching lineation (Fig. 4b, c). Quartz and feldspar have partially recrystallized into fine grains, interlayered with mica-rich layers (Fig. 6). Most crystals of mica occur as ribbons or elongate fishes with aspect ratios larger than 15:1. The mica fishes (Fig. 7a) and elongated mica grains (Fig. 6b–c) are consistently characterized by their orientations with (001) planes (cleavages) parallel or subparallel to the foliation, indicating that the ribbon grains were deformed by slip on (001) planes. It is observed that the ribbon grains are not surrounded by a mantle of fine neograins, suggesting the absence of dynamic recrystallization in the mica. The latter reflects likely a fact that mica are so easily deformed by crystalline glide that dislocation densities and thus the stored elastic strain energy of dislocations cannot be accumulated to reach a critical value to start up grain boundary migration. An alternate explanation for the absence of dynamic recrystallization in mica is probably due to low differential stresses in the rim of the mica crystals, which reduced the tendency to form a recrystallized mantle (Passchier and Trouw, 2005). Figure 7 shows typical microstructural evidence of dislocation creep such as undulatory extinction, lattice rotation, folding and kinking observed in thin sections by optical microscopy. The lattice rotation, folds and kinks are marked by (001) plane delineated by cleavages, which are bent in opposite directions with respect to the axial plane of the fold or the kink band boundary (KBB). The axial plane or the KBB is generally at a small angle to the mylonitic foliation. The mica grains which have undergone high-angle kinking and large lattice bending had usually their original orientations with (001) planes at high angles to the foliation. Kinking and lattice bending made the (001) planes rotate progressively towards the bulk shear plane (Fig. 7c–d). Some kink bands display lenticular shapes (Fig. 7b), which can be interpreted by arrays of tilt boundaries of edge dislocations (McLaren and Etheridge, 1976; Christoffersen and Kronenberg, 1993).

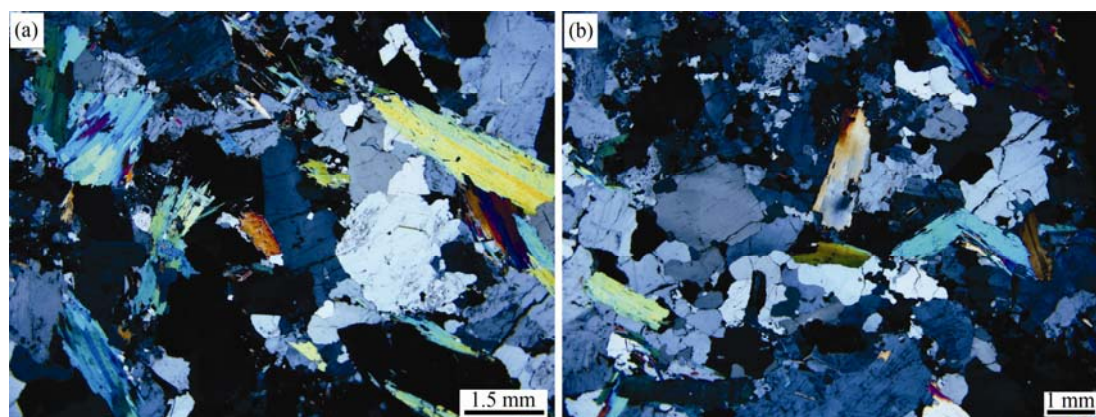


Fig. 5. Typical microstructures of granitic gravels from the undeformed conglomerates of unit LF1.

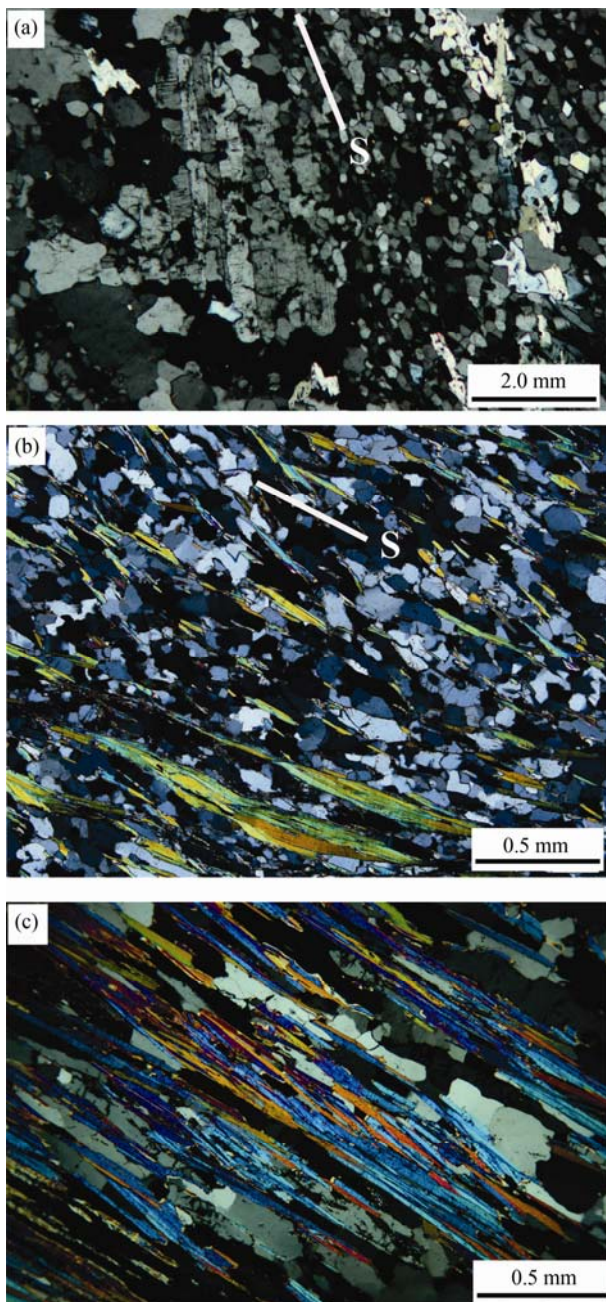


Fig. 6. Microstructures of strongly deformed granitic conglomerates from unit LF2. Quartz and feldspar recrystallized into fine grains (a) interlayered with mica-rich layers (b, c).

Pseudotachylytes in the GCT were preferentially generated in the deformed rocks which are dominantly composed of strong (high fracture toughness) minerals such as quartz and feldspar (Figs. 2, 4). No pseudotachylyte veins have been found in the ophiolite complex, indicating that the serpentinized ultramafic rocks became so weak that aseismic creep prevailed (Moore and Lockner, 2007; Kirkpatrick and Rowe, 2013). The color of the pseudotachylytes, which varies from medium gray, yellowish or reddish brown, brown green, brown dark to dark on the outcrops, generally became lighter with increasing age or progressive shear (Fig. 8). This reflects a

fact that the content and grain size of microlites (e.g., chlorite, biotite, quartz, and albite) in the pseudotachylytes increases with time under the metamorphic conditions. The dark color of the pseudotachylyte is due to the presence of glass, extremely fine-grained biotite and magnetite. The pseudotachylyte has a reddish tinge when magnetite has been transformed to hematite. The difference in color allowed multiple generations of original pseudotachylytes, now mylonites and ultramylonites, to be identified. The mylonitic fabrics formed first and then were overprinted by cataclasite and pseudotachylyte. Subsequently the pseudotachylyte had varying degrees of mylonitic or ultramylonitic overprint. Most undeformed pseudotachylyte veins are within the foliation (Figs. 8–9) or cross-cut the mylonitic fabric (Fig. 4e). Interfingering structures and cross-cutting relationships indicate that newly formed pseudotachylyte veins injected into older pseudotachylyte veins. The repeated injections indicate that coseismic frictional melting events of the strong fault, which generated a relatively large amount of pseudotachylytes (5%–40%), took place cyclically at the same site. Plastic deformation and microlite-formation reactions (i.e., devitrification and crystallization) occurred during the long-term interseismic periods (typically 10^3 – 10^4 years).

The undeformed pseudotachylytes are generally characterized by cross-shaped interpenetrating textures of feldspar and quartz (Fig. 10a–b). The minerals occur as microlites with acicular, dendritic, and skeletal morphologies. The cross-shaped interpenetrating textures preserved even after the glassy matrix was partially transformed to fine-grained chlorites during late devitrification and hydration (Fig. 10c). Spherulite-like structures (e.g., Lin, 2008; Prante and Evans, 2015) were occasionally observed in the undeformed or weakly deformed pseudotachylyte veins. The center of the spherulite, which is generally composed of ultrafine-grained ($<15\ \mu\text{m}$) equant quartz, albite and chlorite, formed by devitrification of glass. In the pseudotachylytes, the feldspar and quartz clasts, whatever their grain sizes, show melt corroded margins (Fig. 10d). Under high magnification, the patches of opaque grains (e.g., magnetite, ilmenite and pyrite) display a palimpsest texture.

Chemical analyses demonstrated that the pseudotachylytic glasses contain less SiO_2 contents (57–65wt%) than their protoliths (65–80wt%). Micro-XRF element mapping also showed higher Fe, Al, K and Mg contents in the mylonitized pseudotachylyte veins than their host rocks. The textural and compositional features described above indicate that the pseudotachylytes formed from frictional heating-induced selective melting within the felsic rocks rather than from direct crushing and comminution of these rocks (Wenk, 1978; Lin, 2008). The minerals with low melting points such as mica (800°C), amphibole and chlorite melted first while the refractory minerals such as quartz (1700°C) and feldspar (1400°C) are survivor clasts in the very fine-grained groundmass crystallized from the melt. Consequently, the pseudotachylyte is depleted in quartz but enriched in biotite (Jiang et al., 2015).

The intensive ductile deformation overprinted the large

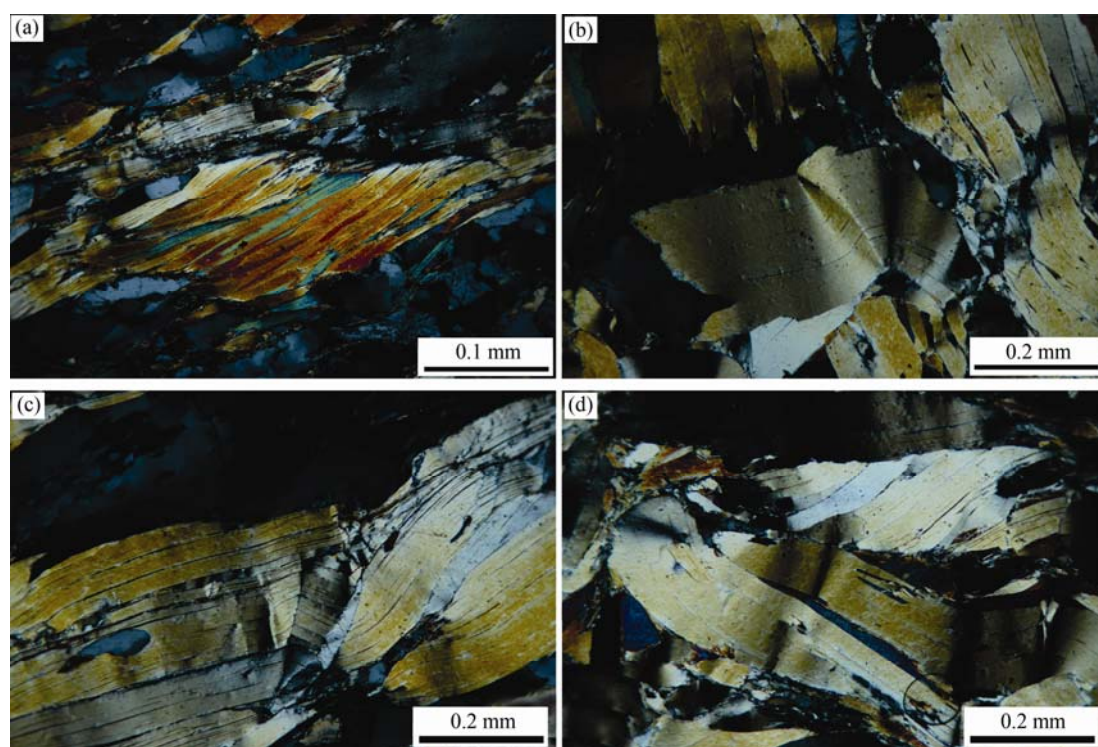


Fig. 7. Optical evidence for dislocation creep of mica in the deformed felsic rocks from the Great Counter Thrust (GCT): undulatory extinction, lattice rotation (folding) and kinks. All images viewed in cross-polarized light.

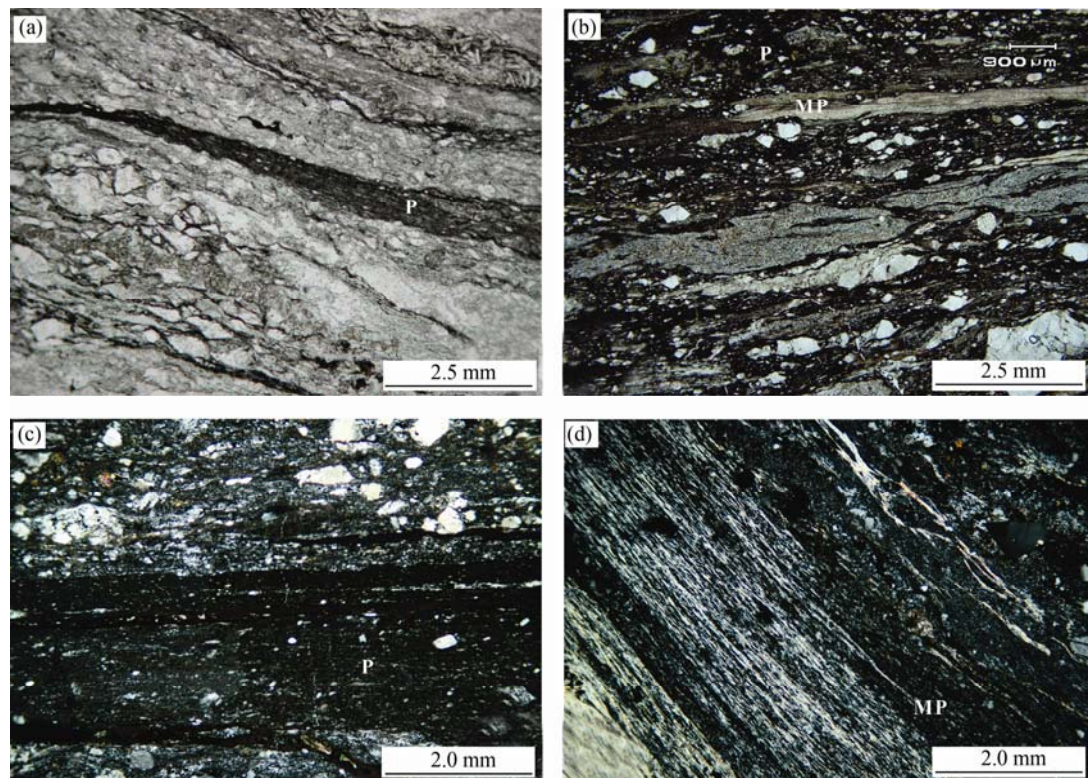


Fig. 8. Photomicrographs of typically deformed (P) and mylonitized pseudotachylytes (MP) from the Great Counter Thrust (GCT) fault zone, southern Tibet.

Strong shape and crystal preferential orientations developed in mylonitized pseudotachylyte (MP) bands (d).

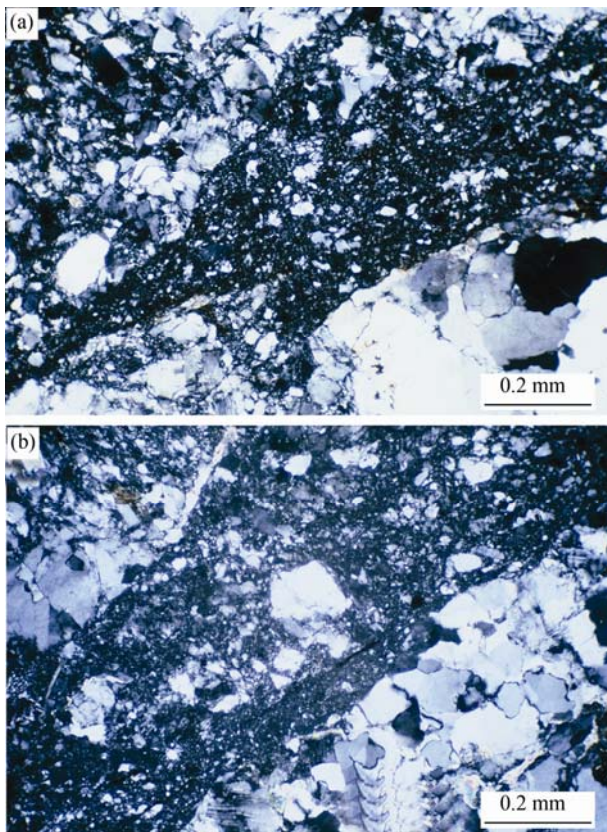


Fig. 9. Photomicrographs of typically undeformed pseudotachylytes from the Great Counter Thrust (GCT) fault zone, southern Tibet.

The undeformed pseudotachylyte consists mainly of albite, quartz and chlorite microlites crystallized from melt or glass, with minor clasts of refractory relict minerals (feldspar and quartz).

volume of pseudotachylytes in the GCT. The pseudotachylyte veins initially crosscutting the mylonitic foliation have been sheared and ultimately converted to mylonite and ultramylonite flow bands in which shear strain has strongly localized (Fig. 8). The mylonitized pseudotachylytic bands are draped around the feldspar porphyroclasts, indicating a large rheological contrast between cataclastically deforming feldspar and plastically deforming pseudotachylyte. The pseudotachylyte veins oriented initially at high angles with the foliation (Fig. 2e), which were formed by either injection of frictional melt generated from the fault-plane-parallel seismic slip or fracture decompression under high shear stresses, have been experienced progressive rotations. The pseudotachylytes injected into the antithetic microfractures of feldspar occasionally escaped from the mylonitization overprint, because the veins were shielded by the strong feldspar, but crystallized in fibrous strain fringes during progressive separation between the fragments. The presence of synkinematic biotite, muscovite, chlorite, albite and epidote indicates that deformation of the pseudotachylytes took place at low greenschist-facies conditions (<450°C).

It is necessary to emphasize that pseudotachylyte veins cutting mylonite and mylonitic overprint of

pseudotachylyte bands coexist in the GCT. The observations present evidence for cycles of ductile deformation-mylonitization, brittle deformation-induced cataclasis and frictional melting during the coseismic slips, and ductile deformation-mylonitization of pseudotachylytes during the long-term (typically 10^3 – 10^4 years) interseismic periods. Variable development of mylonitic fabric derived from pseudotachylyte, cataclasite and mylonite can be observed under optical microscope (Fig. 8). Figure 8a shows a typical example of the transition of mylonite to cataclasite. Retrograde greenschist-facies mylonite transformed to a brecciated cataclasite with the shear zone. A dark band within the rocks is a weakly foliated pseudotachylyte, which contains small clasts of mylonite, cataclasite, and microlites resulted from the devitrification of pseudotachylytic glass.

The deformed pseudotachylytes are cut by quartz or calcite veins, many of which have been folded with complex irregular geometries, sheared (Fig. 11) or transposed into a mylonitic foliation. The low-temperature (<300°C) veins presumably formed as a product of solution-transport-precipitation of quartz or calcite from hydrothermal fluids infiltrated into coseismic extension fractures within the shear zone during the brittle deformation. With post-emplacment of ductile deformation, the veins were folded and sheared in variable amounts, depending on the initial vein geometry, the bulk strain and the rheological contrast between the host rock and the vein material. The veins present clear evidence for processes of rupture in mylonite, healing and sealing due to precipitation and a subsequent ductile deformation. Furthermore, the irregularly deformed veins (Fig. 11b–c) are typically pygmy folds, whose development is generally accepted as related to ductile deformation of vein materials that are more competent than the surrounding host rocks (Ramsay, 1967; Johnson and Fletcher, 1994; Hudleston and Treagus, 2010). Thus, it is reasonable to consider that the foliated pseudotachylytes are rheologically weaker than the quartz or even calcite veins during their deformation.

4 Discussion

The presence of quenched vein margins, vesicles, amygdules, and magmatic flow-induced fold-like structures are generally taken as evidence of frictional melting (Magloughlin and Spray, 1992; Lin, 2008; Kirkpatrick and Rowe, 2013) only when the pseudotachylytes were generated at shallow depths and have not been deformed since their rapid solidification. Clearly this is not the case for the GCT where the majority of the pseudotachylytes have experienced strong ductile deformation under the greenschist-facies metamorphic conditions (<450°C). The shear-induced compaction and subsequent grain growth, crystal plasticity and recrystallization made the evidence obscured or vanished.

The collision of India with Asia started along the ITS at about 50 Ma. Since that time the convergence rate between these two plates slowed from ~16 cm/y to ~5 cm/y (Molnar and Tapponnier, 1975; Molnar and Stock, 2009; Jagoutz et al., 2015). The intensive ductile deformation

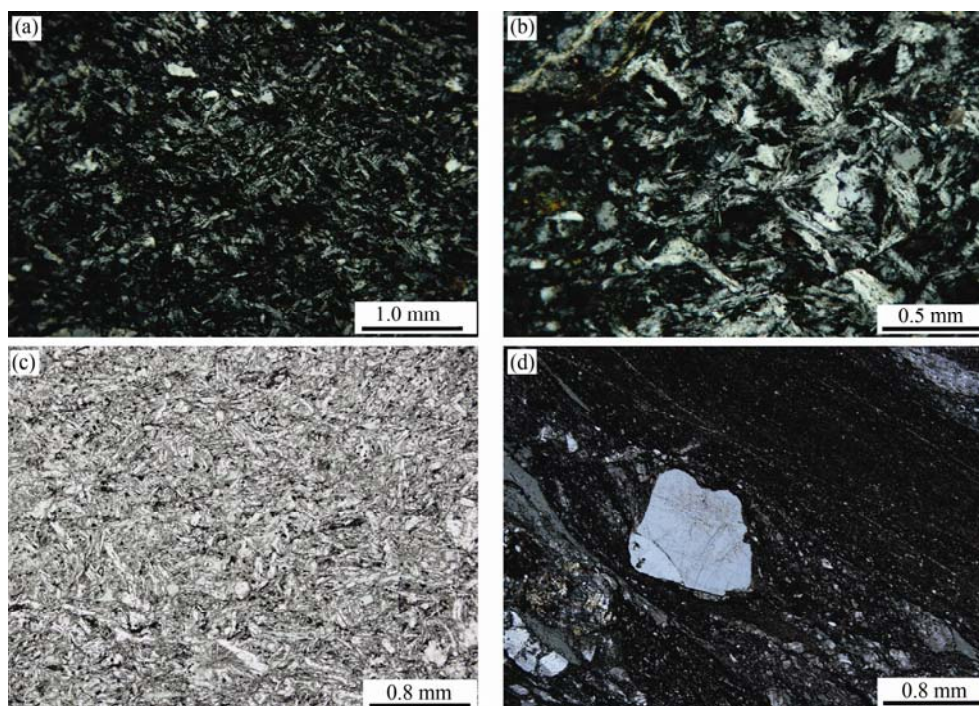


Fig. 10. Photomicrographs showing undeformed pseudotachylyte veins in a felsic rock from the Great Counter Thrust (GCT) fault zone, south Tibet.

overprinting the formation of the large volume of pseudotachylytes suggests that frictional melting played a crucial role in the transition from strong to weak faults in the rocks. Under the greenschist-facies conditions, ductile deformation to accommodate a few centimeters per year of convergence between India and Asia was suppressed in the strong felsic rocks, enabling high differential stresses accumulated to trigger repeatedly large earthquakes that generated cyclically both fault-plane-parallel pseudotachylyte veins and dilatational injection pseudotachylyte veins. As long as the volume fraction of pseudotachylytes became higher than a critical value (~25%, Ji and Xia, 2002), the host rocks started to deform in the ductile manner with shear strains localized strongly into the extremely weak pseudotachylytes. The localization of shear strains was controlled essentially by a drastic drop in strength of the pseudotachylytes due to its extremely fine grains (microlites) crystallized from melt and glass and to the relative concentration of phyllosilicates such as biotite, muscovite and chlorite in the pseudotachylytes. With increasing its volume fractions by cyclical frictional melting, pseudotachylytes formed a network to enhance their connectivity and continuity in the plane and direction of shear. Under shear, the microlites of quartz, albite and particularly phyllosilicate minerals (biotite, muscovite and chlorite) formed strong shape-preferred orientations (SPO) and crystallographic preferred orientations (CPO), leading to further fabric-induced weakening. Microstructural observations demonstrated that the mylonitized pseudotachylytes with well-developed fine-grained foliation should be extremely weak compared to their protoliths. The mixture of water-rich mineral microlites deformed easily by crystal

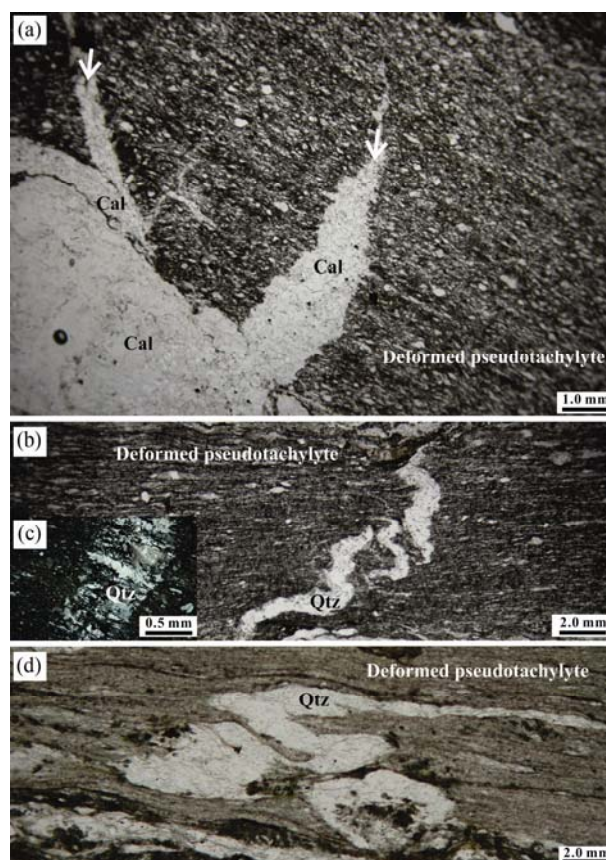


Fig. 11. (a) Hydrothermal calcite veins cut an earlier generation of foliated and mylonitized pseudotachylyte; (b, c) Hydrothermal quartz veins have been folded and transposed in strongly deformed pseudotachylytes.

plasticity, grain-size-sensitive diffusion creep or frictional sliding along very-fine grained foliation composed of phyllosilicates (Collettini et al., 2009; Price et al., 2012). In addition, water taken by frictional melt will be released, during its crystallization and grain growth, to cause hydrolytic weakening in quartz and feldspar crystals. High temperatures from coseismic frictional melt may enable ductile deformation in the host rocks during the cooling of pseudotachylytes (Bestmann et al., 2012). Consequently, the felsic gravels started to deform ductilely although they accumulated much less shear strains than the pseudotachylytes in the same ductile shear zone. It is necessary to point out that the pseudotachylyte-induced weakening is different from the process of friction melt lubrication (Spray, 2005) as the residence time of friction melt (liquid) is only seconds to hours before solidification. Friction melt lubrication occurs only during a large earthquake (Spray, 2005) while pseudotachylyte-induced weakening takes place mainly during the interseismic solid state flow.

These findings provide strong evidence that at the exhumed depths the transition from strong to weak GCT faults within the ITS zone between India and Asia was controlled by the presence of frictional melting-induced pseudotachylytes rather than by high fluid pressure (Zoback et al., 2010; Townend and Zoback, 2000) or the presence of low friction coefficient ($\mu \approx 0.15$) gouge materials such as saponite, corrensite and lizardite (Lockner et al., 2011). These products of metasomatic reactions and alteration becomes unstable above 150–300°C and are unlikely to occur in the fault zone deeper than 10 kilometers where most large destructive earthquakes nucleated under greenschist facies conditions (seismogenic depths: 15–20 km) within the continental crust. Hence, cyclic generation and localized deformation of pseudotachylytes alone appear sufficient to explain the transition of strong to weak fault behaviors. Furthermore, the role of pseudotachylytes played in the motions of plate-bounding faults was underestimated previously due to their rapid transformation to mylonites and ultramylonites by crystal plasticity, mass-transfer processes and reaction-enhanced ductility in the active fault zones, resulting difficulty in recognition (Sibson and Toy, 2006; Kirkpatrick and Rowe, 2013).

Many authors do not discuss the possible conversion of pseudotachylyte to mylonite and ultramylonite, but implicit in their analyses is an assumption that all the mylonite and ultramylonites result from solid-state ductile deformation (e.g., Sibson, 1975; Magloughlin, 1992). Only a few previous studies (e.g., Passchier, 1982; Price et al., 2012) suggested that many pseudotachylyte veins have transformed to mylonite and ultramylonite. Our work builds upon their findings by new observations, from the Indus-Tsangpo suture (ITS) zone, that either pseudotachylyte can postdate much of the mylonite formation or many pseudotachylyte veins can be converted to mylonite and ultramylonite. These relationships suggest that the rocks of the shear zone were uplifted through the brittle-ductile transition where pseudotachylyte, which had a decreased flow strength relative to the adjacent, coarser-grained rocks, were able to

deform plastically after the host rocks were within the brittle or semibrittle regime. The widespread assumption that mylonites and ultramylonites form below the depth of brittle-ductile transition may lead to overestimation of geothermal gradient or incorrect rheological strength profile of the crust.

5 Conclusions

We discovered, for the first time, frictional melting-induced pseudotachylytes in the intensively deformed felsic rocks along the Great Counter Thrust (GCT) within the Indus-Tsangpo suture (ITS) zone in southern Tibet, and provided a self-consistent explanation about the strength evolution and deformation processes of the plate boundary fault between India and Asia. Both field and laboratory observations revealed that pseudotachylytes can induce profound weakness of the thrust fault and controlled the transition from the strong to weak fault behaviors. The extremely low strength of the foliated microlites crystallized from frictional melt or glass in otherwise strong, coarse-grained quartzofeldspathic rocks is sufficient to explain the localization of shear strain, development of ductile shear zones embedded in strong wall rocks, and the transition from the strong to weak faults without invoking the presence of high fluid pressure or low friction coefficient gouge materials within the faults. The role of pseudotachylytes played in the motion of plate-bounding faults most likely has been vastly underestimated due to their transformation to mylonites and ultramylonites by crystal plasticity, mass-transfer processes and reaction-enhanced ductility, resulting difficulty in recognition.

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About the first author



XU Zhiqin is professor in School of Earth Sciences and Engineering, Nanjing University, and member of the Chinese Academy of Sciences. She obtained her Ph.D. from the Université de Montpellier II (1987, France). She has been involved in research on the deformation mechanisms and processes of rocks from various levels of the continental lithosphere and tectonics of major orogenic belts in China (e.g., Tibetan plateau and Qinling-Dabie-Sulu belt). She has played a leading role in the Chinese Continental Scientific Drilling (CCSD) and Wenchuan Earthquake Fault Scientific Drilling (WFSD) projects, and in the Sino-French Collaboration Projects for studying the tectonics of the Tibetan Plateau and its marginal orogenic belts.