Pseudotachylyte Veins in Accretionary Complexes: Melt or Mechanical Wear?

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Pseudotachylyte veins in accretionary complexes: melt or mechanical wear?

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Whether seismic rupture propagates over large distances to generate mega-earthquakes or is rapidly arrested mainly depends on the slip processing within the fault core, including in particular frictional melting or intense grain-size reduction and amorphization. The record of seismic slip in exhumed fault zones consists in many instances in Black Faults Rocks, dark and glass-like-filled aphanitic veins that have been interpreted as resulting from quenching of frictional melts, i.e., pseudotachylytes. Such interpretation has nevertheless been questioned as similar macro to nano-textures have been observed either on intensely comminuted natural fault rocks or on slow creep experiments on crustal rocks, where melting is absent. Here, we report a new dataset of Raman Spectroscopy of Carbonaceous Material analyses, aimed at discriminating the slip weakening processes operating in the fault core during slip. Using high spatial resolution profiles on natural Black Fault Rocks from accretionary complexes and an experimentally calibrated modelling of Raman intensity ratio evolution with temperature, we assessed different scenarios of temperature evolution during fault slip. In the three studied Black Fault Rocks interpreted so far as natural pseudotachylytes, Raman Spectroscopy of Carbonaceous Material results are not consistent with a molten origin and therefore should reflect a mechanical wear during deformation. These results bear major consequences on the dynamics of faulting, as the slip-weakening processes that occur

during seismic slip rely on the extreme grain-size reduction and fluidization rather than melting.

Introduction

Pseudotachylytes have been described for the first time at the beginning of the XXth century as veins filled with black and aphanitic to glassy material¹. They are considered as resulting from frictional melting produced by landslide, meteor impact, or fault rupture²⁻⁴, most often in the shallow and brittle domain of the lithosphere, but in some instances at important depths until to the eclogite facies conditions⁵⁻⁷. Many pseudotachylyte veins are described within fault systems in crustal rocks and are associated with different types of brittly deformed rocks such as cataclasite or fluidized gouge. Pseudotachylyte veins present typical features as injection structures, amorphous matrix or microlites⁵. More recently, Black Fault Rocks have been described in accretionary prisms⁸⁻¹⁴ with macro- and micro-structures similar to the pseudotachylytes reported in crustal rocks⁵. These Black Fault Rocks are described as fault core filling material in zones of intense deformation of the host-rock at low to very low temperature conditions ranging from 160°C to 320°C.

Ambiguity of the microstructures

Whether Black Fault Rocks originate from friction melting or mechanical wear and drastic grain-size reduction is a long-standing issue, due the ambiguity of some of the microstructures associated with pseudotachylytes⁵. Indeed, micro-textural features, such as fluidization and flow textures, amorphous and aphanitic textures or recrystallization of microlites, were considered as a result of ultra-comminution^{6,15-20} or intense fluid-rock interaction in the fault core²¹, without melting. This issue is even more acute in the Black Fault Rocks hosted in low-grade metasediments, which contain large amounts of mineral-bound water: upon slip and

temperature increase, thermal pressurization of released water might reduce friction and prevent from further temperature increase and ultimately from melting^{22–24}.

Insights from RSCM on fault slip processes

Raman Spectroscopy of Carbonaceous Material is a powerful geothermometer widely used in metamorphic petrology to constrain peak-temperature conditions for both regional and contact metamorphism^{25–27}. Raman Spectroscopy has been also used in order to evidence frictional heating during seismic events on natural Black Fault Rocks from accretionary complexes^{28–31} and on experimentally deformed samples²⁸. However, crystallinity of carbonaceous material in intensely deformed rocks may be also influenced by parameters other than temperature. In particular, shear has been shown as responsible for a large increase in crystallinity of carbonaceous material^{32–34}. Therefore, in Raman Spectroscopy studies on both naturally and experimentally damaged rocks, it is difficult to disentangle the thermal and the mechanical effects.

A way out of this conundrum relies on the fundamental difference between temperature and deformation as the strain field might be discontinuous, while the temperature field, because of diffusion, is not. Based on this straightforward idea, we developed a new high-resolution spatialized approach to Raman Spectroscopy, to unravel how the carbonaceous material crystallinity is distributed in space within rock samples. We applied this approach to three Black Fault Rocks described as pseudotachylite in two exhumed accretionary complexes, the Shimanto Belt^{8,12} in Japan and the Kodiak Accretionary Complex^{13,14} in Alaska, in order to discriminate the respective effect of temperature increase and strain, and eventually to decipher the mechanical processes at the origin of the Black Fault Rocks.

Results

Structures

These two complexes investigated here are formed of stacks of units composed either of coherent turbidites or tectonic *mélange* units, bounded by thrust faults^{35,36}. Some of these fault zones (two in Shimanto and one in Kodiak Accretionary Complex), contain Black Fault Rocks bearing characteristic features of pseudotachylytes^{8,12–14}. Black Fault Rocks are vitreous black thin veins, partially or totally devitrified¹¹, which cut sharply across, with straight boundaries, the host-rock that often contains itself brittle microstructures. The two Black Fault Rocks from the Shimanto Belt are millimeter-thick or less but in Kodiak, the Black Fault Rock described by Rowe¹³ reaches up to 30 centimeters-thick. In addition, in contact with meter-sized sandstone lenses, some Black Fault Rocks show structures interpreted as injection structures of a fluidized material perpendicular to the fault core^{8,14} (Figure 1a, 1b and 1c). The filling material is black and has an aphanitic texture (Supplementary Figure 2).

Microstructures

The Black Fault Rock material is characterized by sub-rounded to rounded quartz grains, feldspars and sometimes calcite⁸ embedded in a vitreous black matrix. Grains show both embayment and eroded shape¹⁰ wrapped in the matrix mostly with an illite chemical composition¹¹. Under SEM and TEM, the matrix seems composed of glassy amorphous material with vesicles and amygdules occurrences^{10,13,37}. In the Nobeoka fault vein, EPMA element maps exposes flow textures¹². Inside the matrix, scattered or aligned micro- to nano-microlites and Fe-rich, Ti-rich sulfides are observed^{12–14}. Euhedral microlites of zoned plagioclase have even been described in the Kodiak Black Fault Rock¹⁴.

Polystaged vs single-staged

Moreover, two types of microstructures have been observed for these Black Fault Rocks. Samples from the Shimanto Belt are composed of a single homogeneous layer. In contrast, the thicker Black Fault Rock from Kodiak has a layered structure, visible in both proportion and

size of the clasts embedded in the vitreous matrix (Supplementary Figure 2). Moreover, cathodo-luminescence imaging shows that the clasts embedded in coarser-grained layers are made of the vitreous material forming the adjacent layers Supplementary Figure 2). In this case, these features favorite the hypothesis of a polystage formation process.

RSCM profiles

In this study, the Raman Spectroscopy intensity ratio (i.e., R1 in Beyssac *et al.*, 2002²⁶) and area ratio (RA1 in Lahfid *et al.*, 2010³⁸) were measured over high-resolution cross-sections through the Black Fault Rocks and surrounding host-rock. Intensity ratio evolutions, along each cross-section or a synthetic cross-section compiling the projection of individual cross-sections, show a significant increase, revealing a higher crystallinity inside the veins (Figures 1 and 2; Supplementary Figures 3 and 4). The median intensity ratio in the host rock and the Black fault Rock is 0.500 and 0.600 (Okitsu), and 0.500 and 0.682 (Nobeoka), respectively. In Kodiak, the median intensity ratio in the host rock is 0.454, while it is 0.497, 0.490, 0.507, 0.508 and 0.505 in the five layers forming the Black Fault Rock, labelled I to V, respectively. In the Kodiak Black Fault Rock, the highest median intensity ratio values were not analyzed on the aphyric layer II but on the layers with clasts-and-matrix structures layer III to V. Most importantly, intensity ratios profiles show a discontinuity at the boundary between the Black Fault Rocks and the host-rock jumping from 0.53 to 0.62 in Okitsu, from 0.52 to 0.68 in Nobeoka and from 0.49 to 0.53 in Kodiak, using a local median around few micrometers on each part of the boundaries. Within the Black Fault Rock, the highest values are mostly observed on the inner rims of the Black Fault Rock over the first micrometers (Figures 1 and 2) (Supplementary Figures 3 and 4). Moreover, intensity ratio values measured inside the Black Fault Rocks show an important dispersion marked by a higher standard deviation of the intensity values, from 0.010, 0.004 and 0.009 in the host-rock to 0.063, 0.052 and 0.017 in the Black Fault Rocks of Nobeoka, Okitsu and Kodiak respectively. These Intensity ratios could reach higher values until

to 0.80 even 0.92 for the Nobeoka Black Fault Rock. Finally, fluidization structures described as injection veins show similar values as the ones in the host rock, hence a lower intensity ratio than the core of the Black Fault rocks (Figure 1).

Thermal modelling of RSCM evolution

Model description

In order to interpret the Raman Spectroscopy ratio profiles across Black Fault Rocks, we developed a model to test the effects of heat production and temperature increase during fault slip on carbonaceous material crystallinity. This model combines (1) heat diffusion and (2) kinetics of carbonaceous material evolution during carbonization.

The kinetics of Raman Spectroscopy of Carbonaceous Material signal evolution as a function of temperature was calibrated on the basis of thermal maturation experiments, following Nakamura's procedure³⁹ (Supplementary Note 1).

Heat diffusion modelling is based on the heat equation applied to a 1D system, composed of an infinite matrix embedding a molten layer of thickness h , (= the current thickness of the Black Fault Rock). We considered three idealized endmember cases to model the evolution of the system before and after melting. Case (1) corresponds to a fault zone of thickness h , where heat is dissipated by mechanical work, up to melt the central portion of the fault. Heat production is described as $\dot{E} = \tau \cdot \left(\frac{u}{h}\right)$, with τ (shear stress) and u (slip velocity) constrained from geodetic and seismological models⁴⁰.

Cases (2) and (3) describe the temperature field in a molten layer of thickness h , without/with viscous shear heating, respectively. Heat production is modelled as $\dot{E} = \mu \left(\frac{u}{h}\right)^2$, where μ is the melt viscosity. Slip parameters are subject to large uncertainties, even if mechanical and seismological data provide some constraints on the orders of magnitude. Different slip models,

in terms of velocity u and total duration, were considered, in order to fit the intensity ratio measured in natural rocks.

The geometry and boundary conditions of the model were adjusted on the natural case study of the Nobeoka Black Fault Rock. The thickness of the molten layer of the modelling is fixed to 1mm. The initial temperature and intensity ratio field are uniformed and equal to 200°C and 0.50, respectively. Based on the interpreted melting temperatures for Black Fault Rocks in accretionary complexes in the literature^{11,14}, the temperature of the molten layer is estimated at 1400°C. Complementary information are given in the Supplementary note 1 and 2.

Modelling results

The temperature evolution before melting (Case (1)) is extremely short, as the frictional melting is reached after only few hundredths of second. For this short heating time, the evolution of the intensity ratio of Raman spectra, around 0.003, is not significant (Supplementary Figure 5).

After melting at 1400°C, if viscous shear heating is negligible (Case (2)), inside the molten layer the temperature drops down quickly (in few milliseconds) so that at the center of the layer, the temperature is reduced to 800°C after less than 1 second. In the host-rock, heat diffusion leads to an increase of temperature, locally up to 800°C, but for a very short time. In this scenario, the intensity ratio reaches 0.56 in the center of the molten layer and decreases rapidly laterally, down to unchanged values of 0.50 at the boundary with the host-rock.

The significant intensity ratio increase in the molten layer requires therefore incorporating the production of heat by viscous shear as the fault is slipping (Case (3)). We adjusted the slip velocity to 10m/s and the duration to 0.15s so that the modelled intensity ratios in the center of the molten layer are equal to the natural ones measured in Nobeoka Black Fault Rock (ca. 0.68; Figure 3). In spite of significant heat production by viscous shear, the diffusion of heat away from the molten layer into the cold host rock is extremely efficient, so that sharp temperature

gradients develop within the molten layer (Figure 3a). Therefore, in the outer domains of the molten layer, the intensity ratio remains the same as host-rock values throughout slip (Figure 3b).

Discussion/Conclusions

Shape of modelled vs. natural RSCM ratio profile

The simple parametric models presented here show that frictional melting and viscous shear produce Gaussian shape profiles where gradients in intensity ratio are located within the molten layer, while natural profiles follow rectangular function shapes with major discontinuities coinciding with Black Fault rocks/host-rock physical boundaries. Furthermore, towards the outer boundary of Black Fault Rocks, the modelled peak values are much lower than those in natural cases, even considering extreme conditions of slip and heat production (Figures 3b and 4). Therefore, the Raman properties of carbonaceous Material in the Black Fault Rocks are in contradiction with scenarios where melting occurred.

This conclusion is further supported in polystaged deformation faults such as the Black Fault Rock of Kodiak (Figure 2) (Supplementary Figure 4), where the presence of multiple steps in Raman Intensity ratio is difficult to reconcile with thermal models of multiple melting stages.

Other features plead against as well a control of Raman Spectroscopy of Carbonaceous Material recorded by the temperature field associated with melting. First, intensity ratios retrieved from injection structures are much lower than those in the fault core, again in contradiction with a common origin as a quenched melt (Figure 1). Second, the highest intensity ratio values are mostly measured on the rim of the fault core layer, which is colder than the fault core in thermal models because of heat diffusion.

An alternative model: RSCM ratio profiles record the distribution of strain

Based on these results, the carbonaceous material maturity evolution in terms of values and spatial distribution through the Black Fault Rocks is not consistent with the record of frictional heating^{28–31}. Therefore, the crystallinity evolution is interpreted as a mechanical effect during the co-seismic deformation. The stepwise intensity ratio profiles across the natural Black Fault Rocks coincide well with the microstructure profiles, which reflect strain or strain rate distribution (Figure 4). Contrarily to temperature profiles, strain or strain rate profiles can be discontinuous, as a result of dynamic weakening processes. Moreover, strain, in particular in simple shear geometry, has been shown as responsible of carbonaceous material crystallinity increase during the graphitization stage^{32–34,41}. Our results suggest that strain also occurs at lower temperature conditions, where carbonization is active, to enhance carbonaceous matter evolution towards higher crystallinity.

Indeed, in the nano-structural scale, shear is responsible for the coalescence of pores and the parallelization of the basic structural units that conducts to a more regular organization of the carbon layers and to widen carbon sheets^{32,33}. Therefore, shear will directly catalyze the carbonization reaction and generate higher crystallinity. In addition, deformation processes responsible for the increase of the intensity ratio may correspond to the reorientation of the aromatic carbon sheets in the Black Fault Rocks^{32,33,41}. Moreover, an intensity ratio dispersion has been observed inside the Black Fault Rocks with respect to the host-rock, in agreement with the effects of the shearing during the graphitization^{32,33,41}. This variability plays a major role in the height of the defect bands and deformation will aim to increase the intensity these bands^{42,43}.

From these Raman spectroscopy profiles, we suggest that the Black Fault Rocks are composed of extremely fine-grained material which may be in some cases down to amorphous state, as a result of comminution, i.e., a drastic mechanical work during fault slip. Carbonaceous material crystallinity therefore reflects at the first order a consequence of mechanical processes instead of friction ones with temperature increase. The increase of temperature, if it is the case, is not

sufficient to influence the Raman Spectroscopy ratios within/outside the Black Fault Rocks. As shown by thermal modelling of Case (2), even without considering further heat production by shear heating (Case (3)), the temperature increase required to melt the fault core and the subsequent cooling is sufficient to significantly increase (by 0.06) the intensity ratio in the center of the molten layer, but leaves its outer rim unaffected. The absence of such an anomaly in the natural Black Fault Rocks suggests a modest temperature increase, below the level where melting occurs.

Implications

The nature of processes operating within the fault zone, either melting or mechanical comminution, might ultimately rely on the proportion of available water, contained principally as H₂O mineral-bounds. Natural Black Fault Rocks considered here are hosted in rocks mostly composed of clays and phyllosilicates¹¹ and contain from 5 to 10% H₂O⁴⁴. During the frictional slip, clays and phyllosilicates liberate free water when temperature increases, resulting in thermal pressurization, shear stress reduction and inhibition of further temperature increase up to melting^{23,24}. On the contrary, the low proportion of water-bearing minerals in crustal rocks is probably not sufficient to prevent large temperature increase and melting during frictional slip^{5,45–48}. A close examination of natural Black Fault Rocks is therefore necessary, as similar microstructures may arise from completely different processes of formation. The origin of the material forming the principal slipping zone of fault bears great consequences on fault dynamics. Our observations suggest that the amorphous or extremely fine-grained materials within the Black Fault Rocks result from mechanical comminution. The rheology of comminuted materials varies with a large extent similar to a fluid^{16–18}, so that fluid-like microstructures, such as injection veins, can be observed. From a mechanical point of view, mechanical comminution results, similarly to melting, in an extreme weakening of the fault zone strength during slip. Nonetheless, as their nature is fundamentally different, the weakness

242 of comminuted and molten material may have significantly contrasted characteristics with
243 respect to fault slip. While melting is a thermal problem, involving the balance between
244 frictional energy production and heat diffusion, comminution and amorphization can rather be
245 considered in terms of the competition between mechanical work and the surface/fracture
246 energy. These differences, in terms of physico-chemical processes, bear large consequences on
247 theoretical models of rupture and slip propagation, in particular the critical slip distance,
248 necessary for weakening of the fault core⁴⁹, or more generally the evolution of weakness with
249 slip. To model adequately fault zone properties and dynamics, the rheology of comminuted
250 material appears therefore as a central aspect, yet it is essentially unknown at present time.

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Author contributions BMM wrote this paper and processed all the raman analyzes, RA and HR supervised and reviewed this paper. BMM and RC held kinetics experiments. Numerical modelling was written by BMM and optimized by ELT.

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Supplementary Figures and Tables and Supplementary information are available for this paper.

The authors declare no competing interests.

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Figure 1 | Raman spectroscopy results obtained for the Okitsu Black Fault Rock and its direct host-rocks. a, Intensity ratio evolution along high-resolution cross-sections of the Black Fault Rock ; **b, c,** Close-up views of the fault core and the injection vein and embayment. **d,** Integrated cross-section showing intensity ratio evolution. **e,** Close-up view (red square in (d)) which shows the sharp evolution of the intensity ratio near the fault core.

Figure 2 | Raman spectroscopy intensity ratio results and microstructures obtained for the Kodiak and Nobeoka Black Fault Rocks and its host-rocks. a, Multi-layering and intensity ratio evolution along high-resolution cross-sections of the Kodiak Black Fault Rock b, Microstructures and intensity ratio evolution along high-resolution cross-sections of the Nobeoka Black Fault Rock

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409 **Figure 3 | Thermal and kinetic modellings obtained for a 1mm-thick molten layer where**
 410 **heat is transferred by diffusion to the host rock and is produced in the molten layer by**
 411 **viscous shear heating. a,** Temperature and **b,** Intensity ratio evolution at different times
 412 (curves). Also presented, intensity ratio of the Nobeoka Black Fault Rock. Slip parameters
 413 (slip rate and total slip) were adjusted so that the modelled intensity ratio reaches the natural
 414 values at the center of the molten layer.

Figure 4 | Intensity ratio profile and the amount of strain or strain rate across the host-rock and the Black Fault Rock across the Nobeoka Black Fault Rock (with median and standard deviation shown as black dotted lines). Intensity ratio derived from thermal models of a viscously sheared (case (3)), molten layer is superimposed as a red dotted line. Strain/Strain rate profile is shown as a black bold line. The stepwise shape of natural profile matches strain/strain rate profile, while it stands at variance with thermal models.

Figures

Figure 1

Raman spectroscopy results obtained for the Okitsu Black Fault Rock and its direct host-rocks. a, Intensity ratio evolution along high-resolution cross-sections of the Black Fault Rock ; b, c, Close-up views of the fault core and the injection vein and embayment. d, Integrated cross-section showing intensity ratio evolution. e, Close-up view (red square in (d)) which shows the sharp evolution of the intensity ratio near the fault core.

Figure 2

Raman spectroscopy intensity ratio results and microstructures obtained for the Kodiak and Nobeoka Black Fault Rocks and its host-rocks. a, Multi-layering and intensity ratio evolution along high-resolution cross-sections of the Kodiak Black Fault Rock b, Microstructures and intensity ratio evolution along high-resolution cross-sections of the Nobeoka Black Fault Rock

Figure 3

Thermal and kinetic modellings obtained for a 1mm-thick molten layer where heat is transferred by diffusion to the host rock and is produced in the molten layer by viscous shear heating. a, Temperature and b, Intensity ratio evolution at different times (curves). Also presented, intensity ratio of the Nobeoka Black Fault Rock. Slip parameters (slip rate and total slip) were adjusted so that the modelled intensity ratio reaches the natural values at the center of the molten layer.

Figure 4

Intensity ratio profile and the amount of strain or strain rate across the host-rock and the Black Fault Rock across the Nobeoka Black Fault Rock (with median and standard deviation shown as black dotted lines). Intensity ratio derived from thermal models of a viscously sheared (case (3)), molten layer is superimposed as a red dotted line. Strain/Strain rate profile is shown as a black bold line. The stepwise shape of natural profile matches strain/strain rate profile, while it stands at variance with thermal models.

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