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Tribochemical wearing in S-C mylonites and its implication to lithosphere stress level

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A new approach for revealing the brittle origin of C-surfaces as localized high shear strain zones in S-C mylonites (mylonites with C-surfaces cutting through a mylonitic S-foliation) is presented. A compiled worldwide catalog of width (W) and displacement (D) data for shear zones indicates that ductile mylonites show a constant W/D ratio of $10^{-0.3}$ and ratios of brittle 'cataclasites' vary in magnitude from 10^{-1} to 10^{-3}, implying that the ratio is a diagnosis for discriminating ductile and brittle shear zones. A newly measured W-D data of shear displaced minerals along C-surfaces in granitic S-C mylonites from the Hatagawa shear zone in northeast Japan is added on the worldwide W-D catalog, being plotted on a brittle origin with the high W/D ratio of $10^{-1.5}$. Using this result and a tribochemical wear theory which accounts for wear formation under hydrothermal conditions, C-surfaces in the S-C mylonite might have been formed by cataclastic deformation under the lithosphere stress level of ca. 300 MPa at temperature of 400°C with water for granite. This result suggests a high lithosphere stress level at the depth of the S-C mylonite formation where deformation is predominantly plastic.

1. Introduction

The combination of Byerlee's empirical equation of friction with ductile flow law of rocks determines a strength profile of faults and plate boundaries (Sibson, 1977; Goetze and Evans, 1979). The profile consists of brittle and quasi-plastic regimes, and its transition corresponds to a peak stress regime that faults can hold maximum strength in the crust. Geological observations of exhumed faults indicate that these regimes are associated with cohesive and incohesive 'cataclasite' series fault rocks, and mylonite series fault rocks, respectively. The traditional strength profile has also described the mechanical and seismological implications of geological fault rocks, because the peak stress regime corresponds to a lower limit of microseismicity at the depth around 15 km for an island arc continental plate in Tohoku area, Japan, determined by the Tohoku University group (Hasegawa and Yamamoto, 1994). Shimamoto (1989) proposed a new strength profile in which "semi-ductile" regime (i.e., deformation textures are nearly identical to those developed in the ductile regime, yet the strength is still pressure-dependent) is incorporated between the brittle and the fully ductile regime. He reported that well-defined stick-slips in halite shear zones were recognized within the regime, and showed that the resultant shear-zone texture in halite is similar to a natural S-C mylonites texture which has localized discrete shear zones (C-surfaces) cutting through a mylonitic S-foliation (Berthé *et al.*, 1979; Lister and Snoke, 1984). The C-surface is dominantly parallel to the trace of a shear zone boundary (Berthé *et al.*, 1979; Simpson, 1984; Passchier and Trouw, 1996; Davis and Reynolds, 1996; Ramsay and Lisle, 2000). Based on its textural similarity, Shimamoto (1989, 1993) has argued the hypothesis that the C-surfaces in S-C mylonites originate in brittle manner with a certain amount of stress drop even under predominantly plastic deformation regime. This hypothesis appears to be supported by direct geological observation that the 'ridge-in-groove' slickenside striations and steps develop on C-surfaces in S-C mylonites (Lin and Williams, 1992), suggesting a frictional nature in the plastic regime. Therefore, their optical microtextures of constitute materials on C-surfaces have been considered as an important key for inferring deformation mechanism and stress condition during C-surface formation. However, the constitute materials are too fine-grained to examine their microtextural properties, and there is still few quantitative estimation of lithosphere stress condition under the S-C mylonite formation.

Width (W) and displacement (D) data for brittle 'cataclasites' and ductile mylonites exhibits a remarkably positive, linear correlation between shear zone width and its displacement over seven orders of magnitude in size (Engelder, 1974; Otsuki, 1978; Robertson, 1983; Scholz, 1987; Hull, 1988; Nagahama, 1991). The shear zone width (W) is defined by a grain-size reduction zone, such as a grain-comminuted zone for brittle 'cataclasite' and a dynamically recrystallized zone for ductile mylonites. The W/D ratio for mylonites shows a constant value of $10^{-0.3}$, whereas the ratios for brittle 'cataclasite' vary in magnitude from 10^{-1} to 10^{-3}. A compiled worldwide catalog of W-D data for brittle 'cataclasites' and ductile mylonites suggests that the W/D ratio bounds ductile and brittle nature for the formation of shear zones by the ratio of 10^{-1}. Therefore, the W/D ratio is a diagnosis for

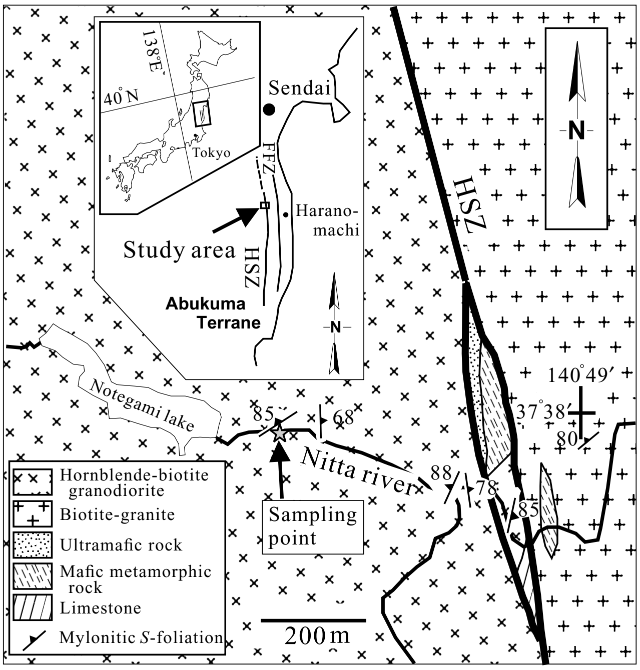

Fig. 1. Geological map with index maps and structural data near the sampling point (star mark) along the Hatagawa shear zone (HSZ), NE Japan (modified after Kubo *et al.*, 1990). FFZ is the Futaba Fault Zone. The HSZ is a sinistral strike-slip ductile shear zone. The sampling point is located along the Nitta river.

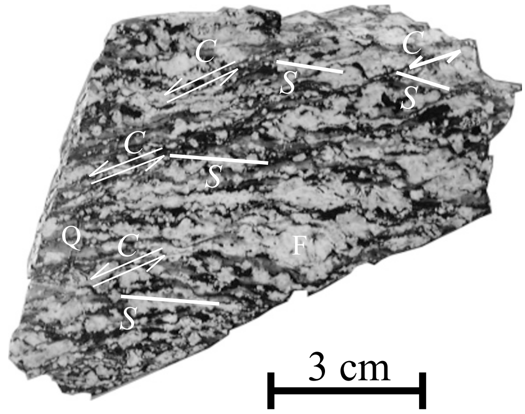

Fig. 2. Hand specimen of S-C mylonite from the Hatagawa shear zone, showing two foliation surfaces: *S* (schistosite) and *C* (cisaillement, shear) surfaces (Berthé *et al.*, 1979). The specimen is cut perpendicular to foliation and parallel to the stretching lineation. Mylonitic S-foliations (white bars) are defined by aligned mafic minerals (black), quartz ribbons (Q) and feldspar grains (F). The *C*-surfaces (white arrows) are discrete, millimeter-thick zones of higher strain, and are cutting through the *S*-foliation. Scale bar is 3 cm.

discriminating the nature of faults. Scholz (1987) explained the variance for brittle gouge by Archard's (1953) wear theory, and estimated the mean lithosphere stress level of 800 MPa from a mean W/D ratio of 10^{-2}. However, this theory does not involve the effect of chemical reactions and ambient temperature during frictional sliding in the presence of water, even though fluids may exist within the crust at seismogenic depths (Zhao *et al.*, 1996). In this paper, we present a new W-D data of shear displaced minerals along C-surfaces in S-C mylonites of granodiorites from the Hatagawa shear zone (HSZ: Fig. 1) in northeast Japan (Shigematsu and Tanaka, 1999; Takagi *et al.*, 2000). Then, we also propose a new wear model under hydrothermal conditions based on a tribochemical wear theory of ceramics. By combining the data of S-C mylonite with the new model, we quantitatively estimate a mean stress level at the depth of the S-C mylonite formation in the lithosphere.

2. Data

We have examined mylonites in the HSZ, located in the Mid-Cretaceous granitoids of the eastern margin of the Abukuma Mountain in northeast Japan (Fig. 1). The shear zone is a sinistral strike-slip ductile shear zone, and has a 1-km wide north-south trending region. Near central portion of shear zone, mylonites possess S-C fabric. S-foliation defines mylonitic sigmoidal foliation and C-surface is cutting through the S-foliation as a localized high shear strain zone (Fig. 2). Field observations show that the C-surfaces are approximately parallel to the trace of the Hatagawa shear zone boundary. Although the terms of "C-surfaces and C'-shear bands" have been widely used in many textbooks (Passchier and Trouw, 1996; Davis and Reynolds, 1996; Ramsay and Lisle, 2000), no C'-shear bands are observed in this S-C mylonites. Since C'-shear bands predate the development of C-surfaces (Will and Wilson, 1989), they have been obliterated if they were present as an intermediate step in the formation of the C-surfaces (Lin and Williams, 1992).

Thin section observation showed that dominant mafic mineral is hornblende, being often displaced along C-surface. We found that an original pair of displaced hornblendes can be determined by same trend of cleavage orientation in the hornblende under optical microscope. The displaced zone shows grain comminution of hornblende, and no clear preferred alignment of comminuted grains. Although mica is also strongly deformed, we found no original pair of the micas along the surfaces. In thin sections, quartz is completely dynamically recrystallized, forming an oblique shape fabric approximately parallel to the overall S-surfaces. Despite all quartz is plastically deformed, the localized shear zone of displaced hornblendes shows no recrystallization due to plastic deformation, but comminuted trails along C-surface (Fig. 3). We conducted measurement of the width (W) of the shear displaced zone and its displacement (D) along the C-surface (as shown in Fig. 3), because the W/D ratio discriminates ductile and brittle shear zones in W-D plot. The width of C-surfaces shows no variation along a millimeter-scale shear zone in the C-surfaces.

The protolith around the HSZ is classified as hornblende-bearing biotite granodiorite. The K-Ar ages for the granitic rocks are about 95–100 Ma (Kubo and Yamamoto, 1990). Mylonite samples from the Nitta River are mainly composed of quartz ribbon, plagioclase porphyroclast, chlorite, biotite, and greenish hornblende in a thin section. Muto and Nagahama (2001) have estimated a temperature of $400 \pm 50°C$ from geothermometry of an amphibolite-facies assemblages (Ernst, 1999) and quartz c-axes fabric transition (Lister and Hobbs, 1980).

Figure 4 summarizes W-D data for brittle 'cataclasites', ductile mylonites and localized shear zones along C-surfaces

Fig. 3. Thin section of a shear displaced mineral (hornblende: Hb) along C-surface in S-C mylonite. Displacement (D) is measured from a distance between each mineral, showing a same orientation of cleavage planes. Width (W) is measured as a localized sheared zone along C-surface (black arrows), cutting obviously through mylonitic S-foliation (black bar).

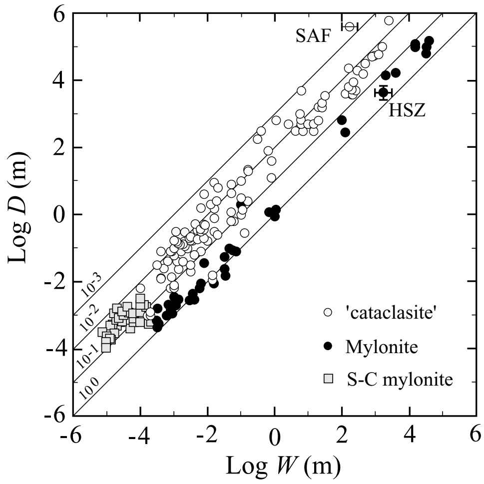

Fig. 4. Log-log plot of width W (m) vs. displacement D (m) for brittle 'cataclasite' (open circles), ductile mylonites (solid circles) and localized high shear strain zones along C-surfaces in S-C mylonites (solid squares). Lines with 45° slopes give constant width/displacement ratios (W/D). This figure consists of a worldwide catalog of ductile and brittle shear zone data, compiled from Engelder (1974), Otsuki (1978), Robertson (1983), Scholz (1987), Hull (1988) and Nagahama (1991). Point SAF is an estimate for the San Andreas Fault in central California (Scholz, 1987). Point HSZ is an estimate from the Hatagawa shear zone in northeast Japan, from which S-C mylonite were sampled. Data of shear displaced minerals along C-surfaces in S-C mylonite are plotted in a brittle 'cataclasite' region with high W/D ratio of $10^{-1.5}$.

in S-C mylonites in a log-log plot. The W-D data of the localized shear zones in S-C mylonites are plotted in a region of brittle 'cataclasites' with high W/D ratio of $10^{-1.5}$, although the W and D data of the HSZ is in a ductile region with the ratio of around $10^{-0.3}$ (Estimated data from Kubo *et al.*, 1990). This result suggests the hypothesis that the shear localization along C-surface has formed in the brittle manner, although we have found no clear observation of 'ridge-in-groove' type slickenside striations and steps on the C-surface.

3. Tribochemical Power-Law Wear Model

Fluids may exist within the crust at seismogenic depths (Zhao *et al.*, 1996; Kasaya *et al.*, 2002). Some previous seismic tomographies found that earthquake nucleation zones might have had low velocities and a high Poisson's ratio that suggested the existence of overpressurized fluids (Gupta *et al.*, 1996; Zhao *et al.*, 1996; Thurber *et al.*, 1997). The existence of fluids enhances an atomic scale interaction of a component of the water with the Si-O bond structure of silicates, leading to a weakening of the rock materials (Griggs and Blacic, 1965; Rutter and Mainprice, 1978; Koch *et al.*, 1989). As a consequence, a chemical process also takes place within the minor shear zone during 'cataclasite' formation, in the presence of water. Under these wet conditions, a tribochemical wear theory (Kitaoka *et al.*, 1997) should be applied to a wear process at seismogenic depths because the theory involves the production of an amorphous silicon oxide coated-layer on the contact asperity due to frictional heat, in the presence of water. The amorphous silicon oxide layer has been observed on the slip surface of quartz and natural fault gouge after sliding (Moody and Hundley-Goff, 1980; Yund *et al.*, 1990). Because this amorphous layer possesses high density of point defects, it might be a possible source of surface charging for the origin of seismo-electromagnetic phenomena (Takeuchi and Nagahama, 2001, 2002). However, this tribochemical wear theory has not been applied to geophysical problems yet, despite of its significance.

All wear theory follows from Archard's (1953) basic model. This traditional model assumes the micromechanisms of friction involving failure of contact junctions by subcritical crack growth (Atkinson, 1984). By this micromechanics, wear particles are removed from the surface by following a frequency factor of asperity fracturing. Scholz (1987) applied this model to 'cataclasites' formation in brittle faulting, and showed that the thickness of wear particles is linearly proportional to displacement and normal stress (σ), and inversely proportional to the hardness (H) of the worn material:

$$W = \left(\frac{A_c}{\rho}\right) \cdot \frac{D \cdot \sigma}{v \cdot H}, \tag{1}$$

where A_c is a frequency factor of asperity fracturing that controls fault activities, ρ is a density of materials, and v is sliding velocity. However, this traditional model does not involve the interaction of frictional and chemical processes that must be required during frictional sliding in the presence of water (Fischer and Mullins, 1994; Zhao *et al.*, 1996).

Table 1. Constitutive variables for frictional sliding experiments of ceramics (Kitaoka *et al.*, 1997) and rocks (Yoshioka, 1986). The variables with asterisks are employed in a following estimation with Eq. (2) of the natural stress level. Some variables have no data from experiments, presented by '—' in the column.

Type	Temperature [K]	C [MPa^{-1}]	m	ΔE [$kJ \cdot mol^{-1}$]
Si_3N_4 (Wet)	393	*$7.6 \times 10^{-7.0}$	—	*21
Granite (Dry)	293	$2.6 \times 10^{-7.1}$	2.08–*2.38	—
Sandstone (Dry)	293	$1.0 \times 10^{-4.0}$	1.00–1.03	—

Thus, we apply a new tribochemical wear theory (Kitaoka *et al.*, 1997) to the seismogenic frictional process. Although the traditional models involve only failures of contact junctions, the wear theory involves the production of an amorphous silicon oxide coated-layer on the contact asperity due to frictional heat. The amorphous oxide layer is removed when the adjacent asperities rupture contact junctions, resulting in further oxidation on the fresh surface. Kitaoka *et al.* (1997) proposed a theoretical equation for a tribochemical wear of non-oxide ceramics in high-temperature and high-pressure water on the basis of the interface reaction of real contact area due to friction:

$$W = \left(\frac{A_c}{\rho}\right) \cdot \frac{D \cdot \sigma}{v \cdot H} \cdot \exp\left(-\frac{\Delta E}{RT}\right), \qquad (2)$$

where ΔE is apparent activation energy of the tribochemical oxidation by water, R is the gas constant (8.3 $J \cdot K^{-1} \cdot mol^{-1}$) and T is the flash temperature during frictional heat. This equation is equivalent to the basic equation of stress corrosion subcritical fracturing (Charles, 1958; Wiederhorn, 1967). However, these models of Eqs. (1) and (2) suggest a linear dependence of the thickness of wear particles on displacement and normal stress.

Nagahama and Nakamura (1994) have shown from the dimensional analysis and Yoshioka's (1986) experimental data that the W/D ratios increase with normal stress in a linear manner for sandstone and in a nonlinear manner for granite. Moreover, they also showed that the nonlinearity of the W/D ratios on normal stress depends on the Mohs' hardness of minerals and sliding velocities from preexisting experimental results (Morohashi *et al.*, 1973a, b). Thus, we propose a power-law form of Eq. (2):

$$\frac{W}{D} = F(\sigma) \cdot \exp\left(-\frac{\Delta E}{RT}\right), \qquad F(\sigma) = C \cdot \sigma^m, \qquad (3)$$

where C is constant ($C = A_c/\rho$) and stress-sensitivity exponent m varies from 1.00–1.03 for dry sandstone to 2.08–2.38 for dry granite. The stress-sensitivity exponent is controlled by the hardness and sliding velocities of contact rock lithologies (Nagahama and Nakamura, 1994). The equation indicates that the ratio increases as temperature and an applied stress increase for the gouge formation, while the increment of apparent activation energies lowers the ratio. This tribochemical power-law model can be also derived from the viewpoint of thermodynamic theory of stress-dependent rate processes for fracture (Yokobori, 1965). In the nonlinear case for granite ($m = 2.08$–2.38), the equation may prove to be an acceptable paleopiezometer of natural faults and the lithosphere, by using W/D ratios of natural faults. (Note that there was erratum between circles and squares in the caption of figure 4 in Nagahama and Nakamura (1994).) For a quantitative estimation, Table 1 summarizes constitutive variables of Eq. (3) from frictional experiments of non-oxide ceramics (Kitaoka *et al.*, 1997) and rocks (Yoshioka, 1986).

4. Discussions and Conclusions

Evans (1990) documented that W-D relations for brittle 'cataclasite' exhibit no linear correlation because they are influenced by various factors, such as fault types, bedrock lithologies, degree of exhumation, and activity of faults. However, there is a power-law relationship with a scattering of W/D ratios. Scholz (1987) has already explained by Archard's wear theory of Eq. (1) that a given rock type and normal stress controls the various ratios, revealing that the ratios for brittle 'cataclasite' increase as an applied stress increases and as a hardness of sliding surfaces decreases. Therefore, the Evans' negative claim is solved by the theoretical interpretation that stress variations affect the factor of fault types and activity of faults, and the hardness involves the effect of bed rock lithologies and degree of exhumation.

Scholz (1987), and Nagahama and Nakamura (1994) summarized the W/D ratio of various natural faults where $10^{-3} < W/D < 10^{-1}$, and proposed the possibility that a natural stress level could be estimated from the W/D ratios of natural 'cataclasite' zones. According to these studies, Scholz (1987) estimated the normal stress of the lithosphere $\sigma \approx 300$ MPa for sandstone and $\sigma \approx 800$ MPa for dry granite by using a linear relationship between normal stress and the average W/D ratio of 10^{-2}. Nagahama and Nakamura (1994) extrapolated the lithosphere stress level of 95 MPa for dry sandstone and 130 MPa for dry granite by using the non-linear relationship with the average W/D ratio of 10^{-2}. However, these estimations have not involved the effect of water on the frictional wear products, being important for natural faults. If we extrapolate the tribochemical power-law wear model to the natural faults for brittle 'cataclasite', the average ratio would require $\sigma = 257$ MPa for granite. This estimation is 2∼3 times higher than the previous non-linear estimation, because we employed an activation energy (21 kJ/mol) of non-oxide ceramics (Si_3N_4) and the stress-sensitivity exponent ($m = 2.38$) on brittle dry-friction of granite.

Non-oxide ceramics are mainly of covalent-type bonding solids, while oxide ceramics, such as silicate minerals of quartz and feldspars, are predominantly ionic-type solids (Davidge, 1979). This difference influences the hardness H of their materials. Tanaka *et al.* (1989) found the Vickers hardness of ionic-type oxide ceramics (silicates) is a factor of 2∼3 smaller than that of covalent type non-oxide ceram-

Table 2. Apparent activation energies for deformation mechanisms of oxide-ceramics (quartz) and non-oxide ceramics.

Mechanism	E (kJ/mol)	Material	References
Pressure solution	35	Quartz	Rutter and Mainprice (1978)
Subcritical crack growth (wet)	53–108	Quartz	Atkinson (1984)
Intracrystaline plasticity	145	Quartz	Koch *et al.* (1989)
Frictional slip (wet)	89 ± 23	Quartz gouge	Chester (1994)
Tribochemical oxidation (wet)	21	Silicon nitride	Kitaoka *et al.* (1997)
Tribochemical oxidation (wet)	21	Silicon carbide	Kitaoka *et al.* (1997)

ics; presumably these properties of rocks would be important yet difficult to determine in natural example. Thus, this hardness reduction would lower the stress estimation for Eq. (3) to 63∼75% of non-oxide ceramics. Figure 4 indicates that the W/D ratio of the shear-displaced mineral in S-C mylonites from the HSZ is about $10^{-1.5}$. If we extrapolate our tribochemical power-law model to the ratio with preexisting experimental data in Table 1, then this ratio would require $\sigma = 423$ MPa (266∼317 MPa for silicates) in 400°C with water to produce the localized shear zones in S-C mylonite. This result is consistent with Shimamoto's implication that S-C mylonite might have been formed at the depth of the "semi-ductile" regime, implying that the lithosphere stress level is about 300 MPa in a frictional nature under the plastic regime.

The traditional strength profile of faults and plate boundaries has revealed that a deep ductile region is mechanically weak and seismically inactive. Thus, one may not believe that such region can store enough strain energy for generating a large shallow earthquake along plate boundaries or deep seismic inland fault. However, Shimamoto's new strength profile implied that S-C mylonite might have been formed at "semi-ductile" regime where deformation is incorporated between the brittle and the fully ductile regime. Our estimation of lithosphere stress level for C-surface sliding is high enough to store the seismic energy even under the "semi-ductile" region. A high normal stress in the lithosphere can produce a certain amount of stress drop by a stick-slip frictional instability (Kanamori and Anderson, 1975). Although an individual slip along C-surfaces we measured is at most centimeter scale in displacement, simultaneous collective C-surfaces slips form a potential weak zone in S-C mylonites. The existence of weak zones may have enhanced stress concentration along C-surfaces in the S-C mylonites under the "semi-ductile" regime where deformation is predominantly plastic, leading to mechanical failure in the earthquake nucleation zone.

Our theory predicts the production of an amorphous silicon oxide coated-layer on the contact asperity due to frictional heat, in the presence of water. This kind of layer have been observed on the C-surfaces with 'ridge-in-groove'-type slickenside striation in natural S-C mylonites from the Eastern Highlands shear zone, Nova Scotia, Canada (Lin and Williams, 1992). In a typical tribological experiment of ceramics, sample is not sealed so that the produced wear material can escape the sliding surfaces easily. Therefore, the oxide layer is removed when the asperities are re-encountered, resulting in further oxidation on the fresh surfaces of asperities. In the case of natural silicate minerals, it is also required to remove the reaction produced materials from sliding surfaces to produce the next fresh surfaces that are ready for the next flash-temperature rise and its resultant oxidation. Lin and Williams (1992) found that the C-surfaces are mostly coated by thin films of very fine-grained phyllosilicate minerals and have a shiny slickenside appearance with 'ridge-in-groove' type striae (Means, 1987). This observation supports our prediction of amorphous oxide layer productions. Moreover, such an amorphous silicon oxide layer has also been observed on the slip surface of quartz and natural fault gouge after sliding (Moody and Hundley-Goff, 1980; Yund *et al.*, 1990). Therefore, 'ridge-in-groove' type striation and step might have removed the amorphous oxide layer during sliding, adding in further oxidation layer. Takeuchi and Nagahama (2002) have argued that hole and electron trapping centers (point defects) in the amorphous layers are an origin of the surface charging mechanism of fracture or slip surfaces of silicon oxides. This amorphous oxide coated-layer on the contact asperity has also a possibility to explain the generation of seismo-electromagnetic phenomena at seismogenic depths.

The values of apparent activation energies E can be used to infer the microscopic mechanisms of deformation that operate at points of contact in frictional test. In general, the apparent activation energy for frictional slip within wet quartz gouges at relatively low temperatures between 24°C and 82°C is 89 ± 23 kJ/mol (Chester, 1994). This value is consistent with the micro mechanisms of friction involving failure of contact junctions by subcritical crack growth (Table 2). However, the value of E for tribochemical wear process of wet non-oxide ceramics is 21 kJ/mol. This value is substantially smaller than those determined for pressure solution, subcritical crack growth, intracrystalline plasticity and frictional slip (Table 2). Thus, the tribochemical process is operated by a new microscopic mechanism involving the production of the amorphous silicon oxide-coated layer on the contact area due to frictional heat, rather than the friction micro-mechanism. In order to determine a natural stress level in fault zones from the W/D ratio of the shear displaced mineral along C-surfaces in natural S-C mylonite, it is necessary to obtain information of frictional properties of rocks from Arrhenius plots for tribological oxidation ($\ln\{(W/D)\cdot(\rho/\sigma^m)\}$ vs. T^{-1}) of granitic rocks in high-temperature and high-pressure water.

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