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Thermal Anomaly and Strength of Atotsugawa Fault, Central Japan, Inferred from Fission-Track Thermochronology

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1. Introduction

Frictional slip induces temperature rise in a fault zone. Abundant frictional heat during an earthquake sometimes produces melt of rocks (i.e. pseudotachylyte; e.g., Sibson, 1975). The amount of heat production along faults provides the essential information to investigate frictional strength of the faults that characterizes the earthquake generation processes. Lachenbruch and Sass (1980) first estimated the coefficient of friction of the San Andreas Fault to be 0.1-0.2 from the measurement of surface heat flow along the fault. Kano et al. (2006) found a temperature rise of ~ 0.06 °C measured in a borehole drilled across the Chelungpu fault six years after the 1999 Chi-Chi, Taiwan earthquake associated with this fault. They found that very low coefficient of friction of 0.04-0.08 can explain the heat anomaly along the Chelungpu fault. The above observations along the natural faults have suggested a very low friction level compared with that of 0.6-0.8 evaluated in laboratory rock friction experiments (Byerlee, 1978).

Fission-track (FT) thermochronology is an effective method to detect heat anomaly caused by past faulting (e.g., Scholz et al., 1979; Camacho et al., 2001; Murakami et al., 2002; Murakami and Tagami, 2004; Yamada et al., 2007a). In order to constrain the frictional properties of faults, d'Alessio et al. (2003) measured apatite FT ages and lengths for samples adjacent to and within the San Gabriel fault zone that is thought to be an abandoned major trace of the San Andreas Fault system active from 13 to 4 Ma. They found no evidence of a localized thermal anomaly in FT data even in samples within just 2 cm of the ultracataclasite, and concluded that either there has never been an earthquake with > 4 m of slip at this locality, or the average apparent coefficient of friction is < 0.4 based on the modelling of heat generation and transport.

In this paper, we estimate the frictional strength of the Atotsugawa fault, central Japan, using the method similar to that used by d'Alessio et al. (2003). In the Atotsugawa fault, Yamada et al. (2009) performed FT thermochronologic analysis at an outcrop without visible pseudotachylyte layers, and revealed a thermal anomaly at a several cm thick gouge whose apatite age is significantly younger than those of other samples in the vicinity. Assuming that the thermal anomaly is cause by frictional heating during a single earthquake, the frictional coefficient and the ancient depth of gouge samples are evaluated by the thermal modelling to satisfy the constraints given by the FT thermochronological data with respect to the geometry and alignment of the gouges in the outcrop.

2. Fission-track thermochronology in Atotsugawa fault zone

The Atotsugawa fault is a right-lateral strike-slip one with a strike of N60°E and almost vertical dip, located in the Hida metamorphic belt, central Japan (Fig. 1). From the trenching surveys, a number of historical large earthquakes were detected along the Atotsugawa fault; the most recent one is the 1858 Hietsu earthquake. The estimate of the magnitude ranges 7.0 (Usami, 1987), 7.3 (Matsu'ura et al., 2006) and 7.9 (Doke and Takeuchi, 2009). Geographical Survey Institute, Japan (GSI; 1997) reported a creeping slip with a rate of 1.5 mm/yr in the central section of the fault.

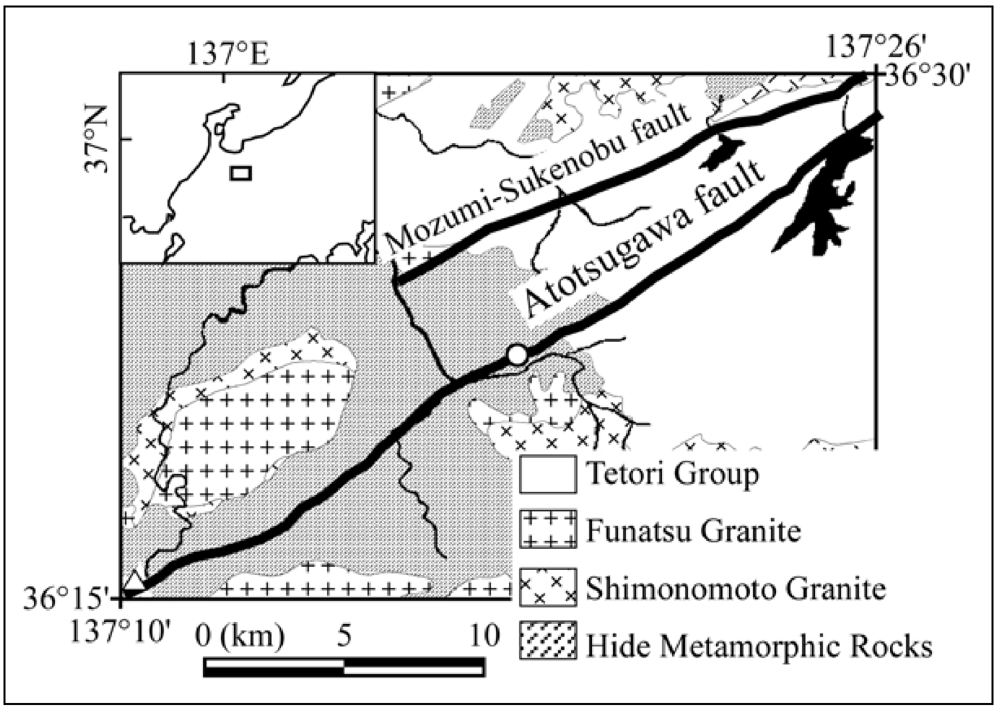

Fig. 1. Distribution of active fault around the Atotsugawa fault. An open circle (centre) and an open triangle (bottom left) symbols indicate the locations of an outcrop and a reference site of R2 in Fig. 2, respectively

In the creeping section, Yamada et al. (2009) performed FT thermochronologic analysis by measuring ages of apatite and zircon grains separated from gouges and fractured rocks at six fracture zones within a 15 m-wide fault zone without visible pseudotachylyte layers (Fig. 2a). This fault zone consists of six fault gouges (name, thickness; gouge-1, 10 cm; gouge-2, 8-20 cm; gouge-3, 8-25 cm; gouge-4, 10 cm; gouge-5, 10-30 cm; gouge-6, 20 cm). FT ages of zircon (c. 120-150 Ma) and apatite (c. 44-60 Ma) for samples except "gouge-1" agree well with emplacement ages for the Funatsu granitic rocks that intruded the Hida Belt (Matsuda et al., 1998). The discordance in zircon and apatite FT ages is interpreted to reflect the rock cooling due to the regional uplift and associated erosion. A thermal anomaly was identified at the gouge sample of "gouge-1" that showed an exceptionally young apatite age (32.1 ± 3.2 Ma, 1σ) with a unimodal FT length distribution, although its zircon age (121 ± 6 Ma, 1σ) was well concordant with other samples (Fig. 2b; after Yamada et al., 2009). The creeping slip observed in the central section of the Atotsugawa fault (GSI, 1997) could be a possible source for this heat anomaly. Such a low slip rate of 1.5 mm/yr, however, causes much smaller increase in temperature (< 20 °C; d'Alessio et al., 2003) in the fault zone. This disagreement can therefore be attributed to the secondary heating induced by frictional slip during an associated earthquake, and the young apatite age possibly gives a younger limit of the initiation of the activity in the Hida Belt.

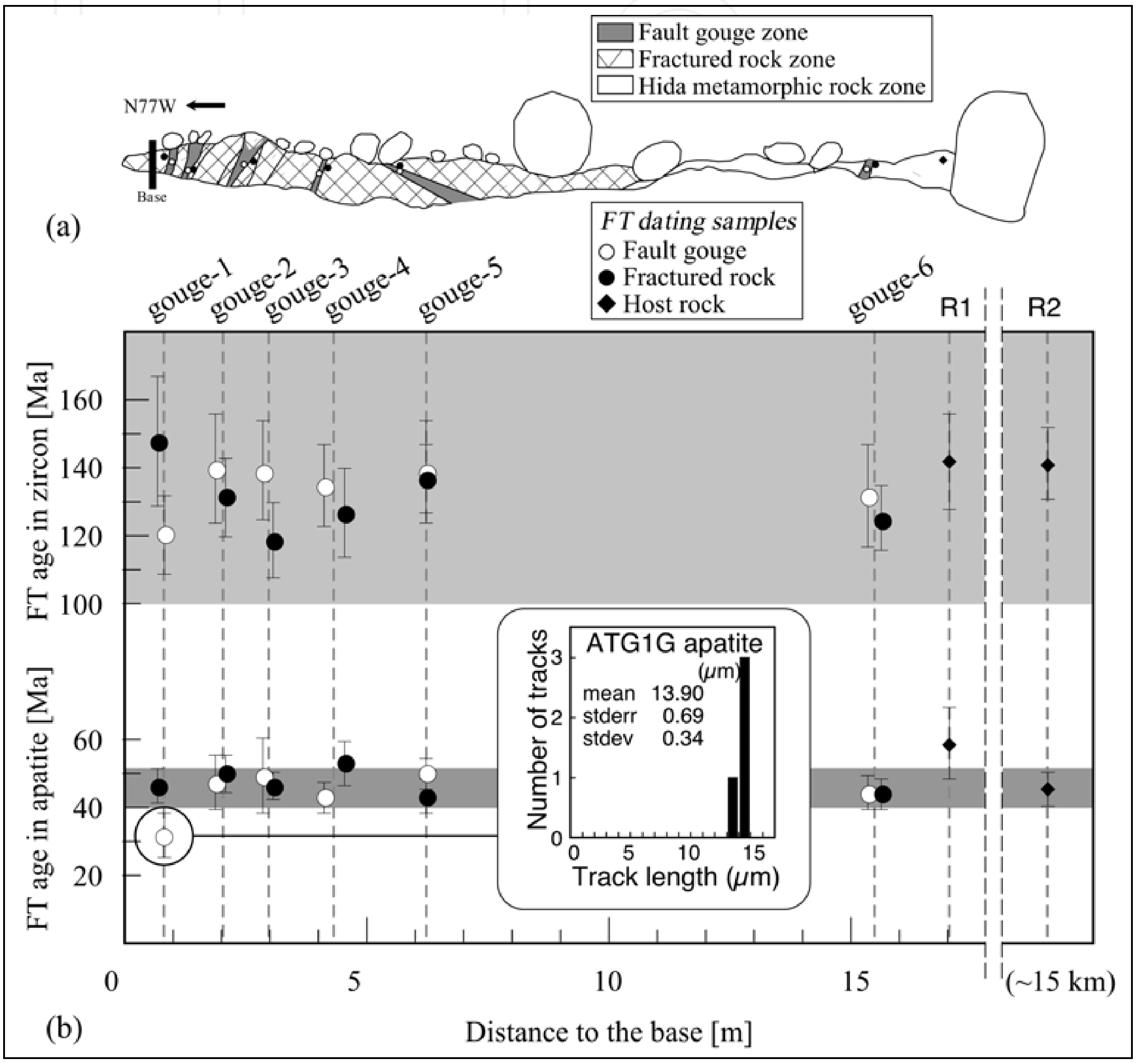

Fig. 2. (a) Sketch of the outcrop of the Atotsugawa fault zone and (b) fission-track age variation in apatite (lower) and zircon (upper) across the outcrop (after Yamada et al., 2009). Open circle, solid circle and square symbols indicate data of fault gouge, fractured rock and host Hida metamorphic rock, respectively. Dashed lines indicate locations of the fault gouge zones. Two reference samples of R1 and R2 (an open triangle in Fig. 1) were also collected where no fractures were observed. Length distribution of apatite FTs for sample ATG1G is also shown. Shaded bands behind the plot indicate the apatite and zircon FT age distributions of the granitic rocks that intrude into the Hida Belt (Matsuda et al. 1998). *Error bars* show 2σ uncertainty in age

3. Thermal modelling associated with frictional heating and estimation of frictional strength

In order to estimate the frictional strength of the Atotsugawa fault based on the FT thermochronological data, we modelled the temporal change in the temperature in and out of the "gouge-1" where an exceptionally young apatite age was found (Yamada et al., 2009). The FT data and the geometry of the occurrence of gouges in the outcrop indicate that the apatite FT age in the 10 cm thick "gouge-1" zone was thermally reset but that in the fractured rock 10 cm apart from "gouge-1" was not. Therefore, the model space for the thermal modelling is composed of a central slip zone of 10 cm thickness and the surrounding rock zone of 10 m thickness with a homogeneous temperature distribution at a certain depth in the initial state (Fig. 3). It is assumed that a single fault slip occurs at a constant rate and all of the frictional work converts into heat. One-dimensional heat transfer model is used to describe the heat diffusion into the surrounding zone at a direction normal to the slip zone. The effect of thermal diffusion by fluid flow is not considered because hydraulic properties of the Atotsugawa fault zone at depth have not yet been investigated.

The equation of thermal diffusion with frictional heat source term for the slip zone is given by

$$\rho_r \cdot C_p \frac{\partial T}{\partial t} = \left(\frac{V \cdot \mu \cdot \sigma_n}{W_c} \right) + \kappa \frac{\partial^2 T}{\partial x^2} \tag{1}$$

where T is temperature, t is the lapse time after a slip occurs, V is the slip rate of the fault, μ is the coefficient of friction, σ_n is the effective normal stress on the fault, C_p is the heat capacity of rock, W_c is the width of a slip zone, k is the thermal conductivity of rock, ρ_r is the density of rock, and x is the distance normal to the fault from the centre of the slip zone. The effective normal stress σ_n is equivalent to the effective overburden pressure given by $(\rho_r - \rho_w) \cdot H \cdot g$, where ρ_w is the density of water, H is depth and g is gravity. For the surrounding zone, Equation (1) without the heat source term (i.e., the first term in the right hand side) is used.

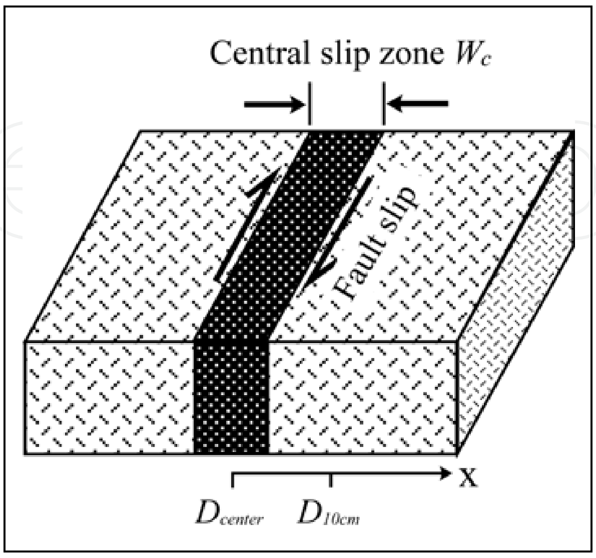

Fig. 3. Fault model for thermal calculation associated with frictional heating. Distance is measured from the centre of the fault

Rock density	2600 kg m^{-3}
Rock heat capacity	1000 J kg^{-1} K^{-1}
Rock thermal conductivity	3.0 W m^{-1} K^{-1}
Water density	1000 kg m^{-3}

Table 1. Parameters used for thermal calculations

Constants of typical physical properties of rocks are used in the thermal modelling as shown in Table 1 (c.f., Schön, 1996). W_c is set as 10 cm that is equivalent to the thickness of the "gouge-1". The initial temperature at a certain depth H is obtained from a geothermal gradient of 30 °C/km (typical value for the upper crust in Japan; e.g., Tanaka et al., 1999) multiplied by H plus a surface temperature of 20 °C, and the temperature distribution over the fault zone is assumed to be uniform. The boundary condition of the temperature at the edge of the model space is fixed at the initial value. Total slip of 5 m long is given for this fault system because the estimate of the magnitude of the associated earthquake ranges from 7.0 to 7.9 (Usami, 1987; Matsu'ura et al., 2006; Doke and Takeuchi, 2009) that corresponds to the total slip of the order of 1-10 m, based on the empirical relationship between the fault displacement and the magnitude (Matsuda, 1975). V is set at 1 m/s (e.g., Heaton, 1990) and therefore the slip duration is 5 sec. Considering the closure temperature of apatite FT (100 ± 20 °C; e.g., Wagner and Van den Haute 1992), H should be shallower than 3 km which corresponds to the environment temperature of 110 °C, and therefore restricted to the three cases of 1, 2 and 3 km for the modelling assuming a geothermal gradient of 30°C/km (e.g., Tanaka et al, 1999).

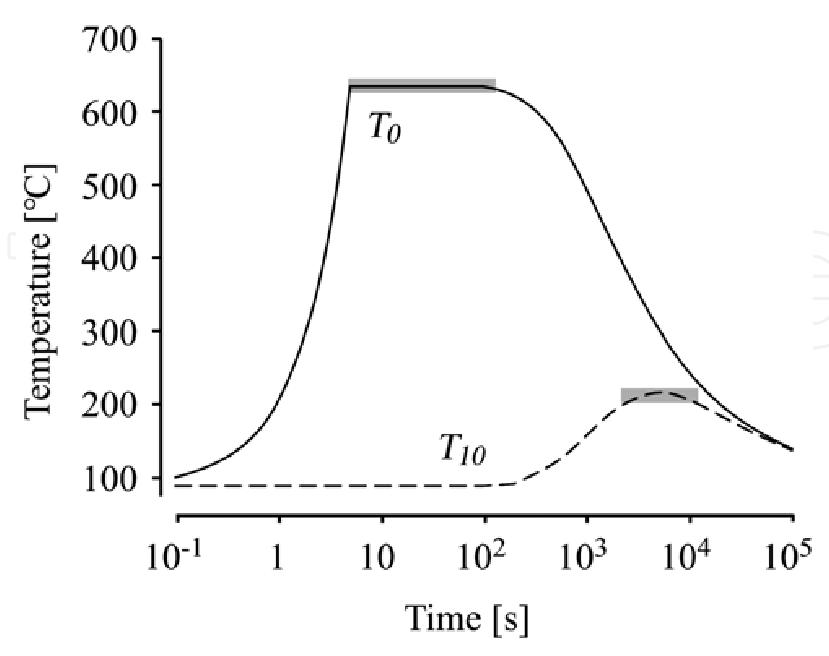

Fig. 4. Temperatures at the centre of the fault (T_0, solid line) and at 10 cm apart from the centre (T_{10}, dashed line) are plotted as a function of time since a slip occurs

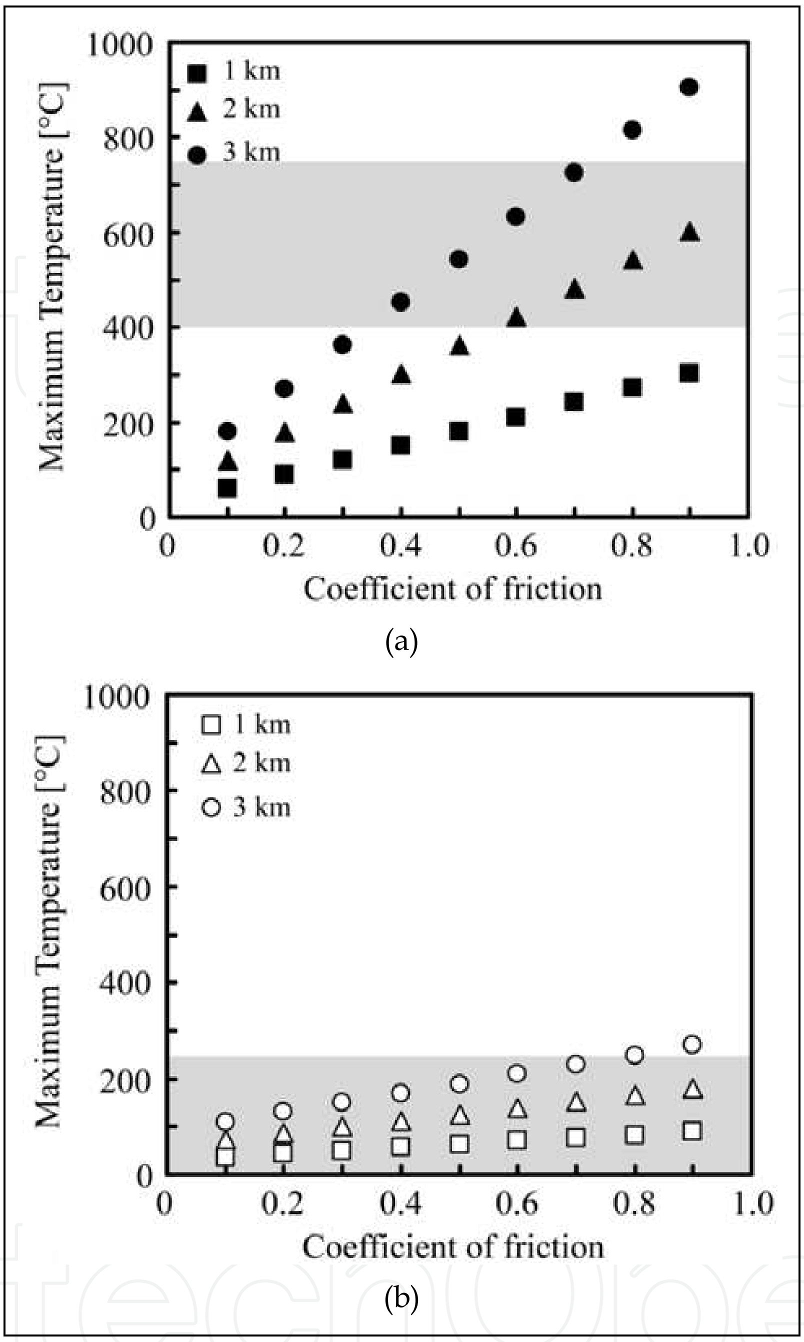

Fig. 5. Maximum temperature at the centre of the fault (T_0; a) and at the location 10 cm apart from the centre (T_{10}; b) during an earthquake are plotted as a function of friction coefficient of 0.1 ~ 0.9 in cases of depth from 1 to 3 km. Square, triangle and circle symbols denote the data at 1, 2 and 3 km, respectively. Shaded areas in (a) and (b) indicate ranges of T_0 (upper) and T_{10} (lower) inferred from apatite and zircon FT thermochronological analyses, respectively

Calculation results of the temporal change in temperature at the two locations of x = 0 cm (D_0) and x = 10 cm (D_{10}) for the combination of μ (0.6) and H (3 km) parameters are shown as representative cases in Fig. 4. These locations are chosen to approximate the positions of the "gouge-1" and a surrounding rock sample, respectively. For any combinations of μ and H parameters, the time during which the temperature in a specific location is maintained at its maximum is almost invariant. The temperatures at D_0 and D_{10} are preserved at the maximums of T_0 and T_{10} (named T_{max0} and T_{max10}) for the order of ~10^2 sec and ~10^4 sec, as indicated by shaded bands in Fig. 4, respectively. Fig. 5 shows the variations of T_{max0} and T_{max10} for the combinations of μ (0.1-0.9) and H (1-3 km) parameters.

Whether FTs in apatite and zircon are annealed or not depends on the temperature and duration of heating. Assuming that the frictional heat caused by an associated single palaeo-earthquake event was responsible for the thermochronologic difference between the “gouge-1” and other samples, calculation results above indicate that the effective heating duration for the samples at D_0 and D_{10} at T_{max0} and T_{max10} are estimated as the order of ~10^2 sec and ~10^4 sec, respectively. Note that the effective heating time is significantly longer than the slip duration, and that FTs in minerals in the distance to the frictional centre are not necessary annealed instantly due to the frictional slip event. The estimates of heating durations and the kinetic relation of time-dependent FT annealing temperature of apatite and zircon (Laslett and Galbraith, 1996; Yamada et al., 2007b) give the following constraints on the T_{max0} and T_{max10} at the secondary heating event (Yamada et al., 2009). For the D_0 sample, the fact that apatite FT age was totally reset although zircon FT age was not indicates that T_{max0} is in the range of 400°C to 750°C (for the heating duration of ~10^2 sec). For the D_{max10} sample, the fact that both apatite and zircon FT ages were not reset indicates that T_{max10} does not exceed 250 °C (for ~10^4 sec). These constraints on T_{max0} and T_{max10} are satisfied with the limited cases of $\mu > 0.6$ for $H = 2$ km, and $0.4 < \mu < 0.7$ for $H = 3$ km, shown as shaded areas in Fig. 5.

4. Discussion

The effect of the pore water is not taken into account in the modelling above. If the pore water exists at the “gouge-1” zone, the temperature will be less than that in the dry condition calculated above, because the pore pressure decreases the stress applied on the fault and the frictional heat is diffused by fluid flow. Therefore, the estimate of the frictional strength in the dry condition can be regarded as a lower bound. The increase in the total amount of slip with the same slip velocity will considerably raise the temperature in the fault zone. If the total amount of slip is doubled compared with the case for the above calculation (= 5 m), the estimated increase in T_0 and T_{10} is almost doubled and the estimate of the coefficient of friction is reduced to almost half. Even in this case, however, the estimated coefficient of friction is still large ($\mu > 0.3$ for H = 2 km; $0.2 < \mu < 0.4$ for H = 3 km) compared with that of 0.1-0.2 (Lachenbruch and Sass, 1980) and 0.04-0.08 (Kano et al., 2006).

Our estimates are obtained by assuming that the thermal anomaly found in “gouge-1” zone is attributed to the frictional heating during a single earthquake associated at ~32 Ma (Yamada et al., 2009). Although a number of earthquakes should have occurred thereafter along the Atotsugawa Fault that remains active to date, an amount of heat generated by each of these quakes might be insufficient to reduce FT length in apatite because the partially annealed tracks are not observed for the "gouge-1" sample. The coefficient of friction for the earthquakes occurred after 32 Ma are, therefore, inferred as < 0.6 for $H = 2$ km, and < 0.4 for $H = 3$ km. In addition, the effect of accumulated residual heat generated by a number of earthquakes should be taken into account if the next heat generation may occur before the temperature in the fault zone is reduced to the ambient temperature due to the thermal diffusion in rocks. This effect should, however, be negligible considering the recurrence interval of general active faults in Japan, ranging from 1000 to 10000 years

(Research Group for Active Faults of Japan, 1991) that would be sufficiently long for the thermal diffusion.

Our modelled estimates of the coefficient of friction are approximately consistent with that obtained in laboratory friction experiments on rocks (Byerlee, 1978). As for the Atotsugawa fault, Mizoguchi et al. (2007) obtained the similar frictional strength of 0.5-0.6 by laboratory friction experiments using fault gouge samples taken from the Atotsugawa borehole core samples at a depth of 326 m, located near to the FT samples of Yamada et al. (2009). This coincidence of frictional strength between the nature and laboratory has rarely reported in the past. In previous studies, frictional strengths of natural faults are estimated much lower than those in the laboratory (Lachenbruch and Sass, 1980; Kano et al., 2006; d'Alessio et al., 2003). At the outcrop of the Atotsugawa fault in Yamada et al. (2009), however, the other five gouges were not heated enough by frictional slip to reset their ages. We suggest that the frictional strengths of the fault during earthquakes when the other gouges were activated were less than that for the "gouge-1". The variety of frictional strength of fault with every event might reflect the complicated earthquake generation processes.

5. Conclusions

The fission-track analysis on fault-related rocks collected from a outcrop of the Atotsugawa fault without visible pseudotachylyte layers revealed that the apatite FT age of the a gouge sample is exceptionally younger than those of the surrounding other rocks (fault gouge, fractured rocks and host rocks) in the vicinity, although the zircon FT age is well concordant with other samples. To explain the thermal anomaly identified at this gouge sample, we modelled the temporal change in the temperature in and out of the gouge after an associated earthquake generated the frictional heat. The calculation results indicate that the effective heating time is significantly longer than the slip duration, and that FTs in minerals in the distance to the frictional centre are not necessary annealed instantly due to the frictional slip event. The estimate of frictional strength for the "gouge-1" is larger than 0.6 for H = 2 km, and between 0.4 and 0.7 for H = 3 km, which is similar to that obtained in laboratory friction experiments using the gouge samples taken from the Atotsugawa Fault.

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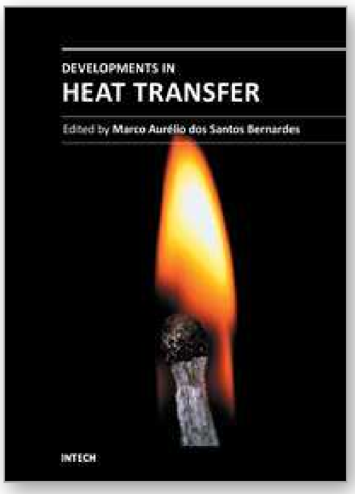

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