The assessment of fault activity is necessary to mitigate against damaging earthquakes. To adequately assess long-term fault activity, a new technique that complements chronological investigations is required. Here we examine the applicability of the slip tendency (ST) method, based on physical models, to assess fault activity in Japan. We computed the ST using a friction coefficient of 0.6 for the faults, a common friction coefficient for rocks, and the stress state estimated from earthquake focal mechanisms in northeastern Japan. Calculated ST values are high for the most active faults (e.g., the Senya segment) and are low for inactive fault (e.g., the Sakunami–Yashikidaira segment). Therefore, we propose that the ST method can be applied in assessments of fault activity. However, the ST method sometimes underestimates fault activity, and we have explored the necessary input parameters to obtain reliable results. To use the ST method, the determination of these parameters is critical for the robust assessment of fault activity based on physical models.

Key Words: long-term fault activity, slip tendency, active fault, northeastern Japan

1. INTRODUCTION

The reliable assessment of fault activity is important in reducing damage caused by earthquakes. This is a problem of particular significance to Japan, as it is located on an active plate convergent margin. Geological faults that have been active during the Quaternary Period are termed “active faults.” The government of Japan has founded “The Headquarters for Earthquake Research Promotion,” which disseminates information related to earthquakes and their hazards to society (http://www.jishin.go.jp/main/index-e.html), because the demand for a more thorough understanding of fault activity is increasing. Furthermore, the assessment of long-term fault activity (100,000+ years) is necessary to identify suitable sites to potentially locate important infrastructure, such as high-level radioactive waste repositories. However, the assessment of fault activity, particularly long-term activity, is difficult. A new technique that adds to our understanding of fault activity, beyond the conventional assessment of fault activity based on chronological investigations, is therefore beneficial. Here, we examine the applicability of a method based on physical models for the assessment of general and long-term fault activity (Fig. 1).

The conventional and most widely used method for assessing fault activity is based on chronological investigations such as studying the recurrence intervals of fault activity (Fig. 1-a). Identification of active faults by geomorphological and/or geophysical observations and estimating the recurrence intervals of faulting through trenching and/or boring studies are two basic ways of studying fault activity. However, there are several difficulties that occasionally arise when employing these methods. First, dating may be difficult when no suitable material is present that is amenable to radiometric or tuff dating. For example, it is difficult to determine the timing of
fault activity from faulted granitic basement that has not been covered with Quaternary sediments. Second, the distinction between active and inactive faults is not always clear. Although an active fault is defined as a fault that has experienced Quaternary displacement,\(^1\) this may not be a suitable criterion in practice for identifying active faults. For example, the Nuclear Regulation Authority of Japan is proposing new standards for determining active faults involving two time thresholds (i.e., late or middle Pleistocene).\(^4\) This will be a complex problem, particularly in defining the time threshold for the long-term evaluation. Third, it becomes more difficult to determine fault activity on older faults, because, for example, the geomorphic evidence of a previous fault activity can be removed by erosion. Moreover, anthropogenic modification can eliminate the evidence of past fault activity, particularly in urban areas. Finally, in order to estimate future fault activity based on chronological evidence, we need to hypothesize that earthquakes occur in specific and relatively constant recurrence intervals, behaving as a “characteristic earthquake.”\(^5\) Clearly, this is not always the case, as some faults change their behavior during their history, such as during inversion tectonics.\(^6\) Furthermore, recent studies have revealed that certain fault properties, including friction\(^7\) and fault dip,\(^8\) change over geological timescales. The tectonic stress regimes that control fault activity have also been observed to evolve over longer timescales (100,000+ years).\(^9\) As such, changes in the characteristics of fault activity related to temporal changes in fault properties and stress fields need to be considered when estimating long-term (100,000+ years) fault activity. In this case, it would be ideal to complement the chronological method by developing another method for estimating fault activity.

Here we introduce a physically based method for estimating fault activity to complement the chronological approach (Fig. 1-b). The simplest and most widely used physical model to simulate fault activity is the Coulomb criterion\(^10\) (Fig. 2). Morris et al.\(^11\) introduced the concept of “slip tendency” (ST) to represent the relative likelihood of fault slip, based on an assessment of frictional sliding on the fault surface. A method of assessing fault activity based on physical models has three main advantages. First, the parameters used in the assessment, such as stress state and fault orientation, can be directly measured and are independent of any chronological information. Second, a physically based method can be applied to the long-term assessment of fault activity. The long interval of fault activity does not greatly affect a physically based method, because such a method does not change over time. Third, a physically based method can be applied to cases where the fault properties or tectonic stress regimes have changed over time, which is important when trying to understand long-term future changes in fault activity. In such a case, fault activity under new fault conditions or tectonic regimes will differ from previous activity. Finally, a physically based method can evaluate fault activity in an evolving tectonic setting by inputting the estimated new properties of the fault or stress field. These advantages in estimating fault activity via a physically based method allow the limitations of the chronological method to be overcome.

A previous study assessed the applicability of the ST for evaluating active faults in the Japanese islands.\(^12\) A detailed stress field, obtained from micro-seismicity surrounding active faults, was used, yielding high-resolution results.\(^12\) However, the area of micro-seismicity was limited; consequently, only \(~37\%) of the active faults in Japan were evaluated.\(^12\) Furthermore, the authors suggested that anomalous pore fluid pressure could promote fault activity even
when the calculated ST was low. This kind of discrepancy can be significant when we consider the long-term activity of a given fault, because the uncertainty of each fault parameter can increase over time. Thus, to apply the physically based method to the evaluation of long-term fault activity, we need a generalized method that can be applied to all the faults we want to assess, and we need to know which parameters can affect and/or lead to erroneous ST values. In this paper, we examine the applicability of the physically based ST method in assessing fault activity on all known active faults in northeastern Japan, using the regional-scale stress field to check the robustness of this method. We also evaluate the effect of several parameters that can affect and/or lead to erroneous ST values.

2. SLIP TENDENCY

The Coulomb failure criterion is one of the most widely used physical models to understand rock failure and fault slip.\(^\text{10}\) The Coulomb failure criterion states that rock failure or fault slip occurs along a plane if the following condition is satisfied:

\[
\tau = C_0 + \mu (\sigma_n - P_f)
\]

(1)

where \(\tau\) is the shear stress acting on the plane, \(\sigma_n\) is the normal stress acting on the plane, \(\mu\) is the friction coefficient of the plane, \(P_f\) is the pore fluid pressure acting on the plane, and \(C_0\) is the cohesion of the rock or fault plane. The crustal stresses (\(\tau\) and \(\sigma_n\)) are factors acting external to the fault, whereas \(\mu\) and \(C_0\) are factors inherent to the fault itself. Equation (1) provides a means of estimating fault activity based on the Coulomb failure criterion.

In this study, we consider existing active faults with a discrete fault plane. Fault cohesion is therefore assumed to be significantly lower than the cohesion obtained from intact rock experiments (~50 MPa\(^\text{13}\)). This assumption allows us to ignore the cohesion term in Equation (1), which simplifies to (illustrated in Fig. 2)

\[
\tau = \mu (\sigma_n - P_f)
\]

(2)

The pore fluid pressure suppresses the normal stress on the fault surface as follows:

\[
\sigma_n' = \sigma_n - P_f
\]

(3)

where \(\sigma_n'\) is effective stress. The range of pore fluid pressure is \(P_{f0} \leq P_f \leq P_{f\max}\) (Fig. 2). The minimum fluid pressure (\(P_{f0}\)) is the background fluid pressure when the fault is activated. This minimum fluid pressure is generally assumed to equal the hydrostatic pressure. Conversely, the maximum fluid pressure (\(P_{f\max}\)) represents the non-hydrofracture condition (\(P_{f0} \leq \sigma_s\)); stationary hydrofracturing is taken to be rare in our target area.

Slip is likely to occur on a surface when the resolved shear stress (\(\tau\)) equals the frictional resistance to sliding, which is proportional to \(\sigma_n\) (Equation 2). The ST of a fault plane is defined as the ratio of shear stress to normal stress on the plane surface for a cohesion-less fault as follows:

\[
T_s = \frac{\tau}{\sigma_n'}
\]

(4)

where \(T_s\) is the slip tendency. Consequently, the likelihood of fault slip is high when the ST is high, and vice versa. If the stress tensor is known, then the shear and normal stresses acting on the fault plane can be calculated and the ST directly determined. However, typically, only the orientation of the principal stress and the principal stress difference ratio, \(\Phi = (\sigma_1 - \sigma_3)/(\sigma_1 - \sigma_3)\), are known\(^\text{15}\) (the stress difference ratio is denoted by \(R\) in some previous studies\(^\text{15}\)). This is particularly the case when the stress field is derived using inversion schemes from geological slip measurements and earthquake focal mechanisms.\(^\text{15}\) However, even in this situation, the ST can be computed from the criterion for frictional sliding, by assuming that the frictional sliding envelope is tangential to the Mohr circle.\(^\text{15}\) Moreover, we use the normalized ST with the maximum ST given the input stress. A normalized ST varying between 0 and 1 is defined by dividing the ST by its maximum possible value (i.e., \(T_s' = T_s/T_s^{\text{max}}\)). In this equation, \(T_s'\) is the normalized ST, \(T_s\) is the calculated ST from Equation (4), and \(T_s^{\text{max}}\) is the maximum ST on the fault plane that has the most favora-
ble orientation relative to the principal stress orientation. Subsequently, in this paper, we refer to $T_s$ as “slip tendency.”

Several previous studies have employed the ST in their analyses, including: (1) a seismotectonic and volcanic hazard assessment of fault activity related to volcanism\(^{16}\); (2) three-dimensional fault models of the Roer Valley rift system, Netherlands\(^{17}\); (3) the frictional reactivation theory of faults and the validity of fault-slip analysis\(^{18}\); (4) mechanical and structural controls on aftershock rupture planes\(^{18}\); and (5) the origins of complex fault patterns induced by evaporation dehydration and cyclic changes in fluid pressure.\(^{19}\) Moreover, new techniques based on the ST have been recently developed.\(^{20}\) In the following section, we examine the suitability of the ST in assessing fault activity in Japan, and discuss its potential applications.

3. APPLICABILITY OF THE SLIP TENDENCY METHOD TO ACTIVE FAULTS IN NORTHEASTERN JAPAN

The ST values were calculated for faults in northeast Honshu that are considered to be active, from data compiled by the National Institute of Advanced Industrial Science and Technology and listed in the Active Fault Database of Japan (https://gbank.gsj.jp/activefault/index_gmap.html). The interpretation of the ST values is compared with the known characteristics of these faults.

(1) Data sets

Three parameters are necessary to compute the ST: the orientation of the fault plane (i.e., strike and dip), the frictional coefficient of the fault plane, and the stress state. We used the following data sets to compute the ST on 71 active faults in northeastern Japan (Tohoku region).

We used the simplified fault strike and dip information for active faults listed in the Active Fault Database of Japan compiled by the National Institute of Advanced Industrial Science and Technology assuming the fault plane has a planar geometry.

Given that there were no compiled data sets of friction coefficients for the target faults, we used a typical frictional coefficient for rock of 0.6, as obtained from the laboratory experiments of Byerlee.\(^{13}\)

The orientation of the principal stress and stress difference ratio ($\phi$) are necessary to compute the ST. The maximum compression stress ($\sigma_1$) was almost horizontal ($\sigma_1$, as oriented E–W) for the whole of northeastern Japan prior to the 2011 off the Pacific coast of Tohoku Earthquake (11 March 2011).\(^{21}\)

Accordingly, we analyzed the stress field by employing a stress inversion method\(^{22}\) across the region, spanning 37.0–41.0°N and 139.5–142.0°E, which covers the Tohoku region of northeastern Japan. We used focal mechanism data publicly available from the National Research Institute for Earth Science and Disaster Prevention (NIED), Japan. The data correspond to 125 earthquakes that occurred between 1 January 1997 and 31 December 2007. All the foci were located in a depth range of 5–23 km,
and had magnitudes of > 3.3. The stress obtained from the analysis has $\sigma_1$ and $\sigma_3$ orientations of 280.2°/4.6° and 060.3°/84.0° (azimuth/plunge), respectively, with a stress difference ratio of 0.56 (Fig. 3).

Yukutake et al.12) also evaluated the ST in Japan using fault orientation and a friction coefficient, as we have done here. However, these authors obtained the stress field using only the focal mechanisms that were close to the targeted faults (i.e., a 0.1° mesh in latitude and longitude). Their approach works well for calculating accurate ST values on each fault with high spatial resolution where high local seismicity is recorded. However, low seismicity surrounding a targeted fault will lead to a poorly constrained stress field and the inability to calculate ST values. We therefore evaluated all active faults by assuming a homogeneous stress field for northeastern Japan. This moderate limitation for the stress state enabled us to evaluate the long-term fault activity of the region, although with some uncertainty.

(2) Calculation of ST for active faults in northeastern Japan

We calculated the ST with a frictional coefficient of 0.6 and the same regional stress pattern obtained as described above (Fig. 3) for all of northeastern Honshu, assuming hydrostatic pressure (i.e., $p_f = p_{ho}$ in Equation (2)). High ST is observed on NNE–SSW striking faults that are perpendicular to the $\sigma_1$ direction and dip at 40°–60° (Fig. 4). In contrast, low ST is obtained for steeply dipping (~90°) or low-angle (~0°) faults.

The ST for active faults in northeastern Japan is generally high (Fig. 5). The Senya segment (Fig. 4-a, 5-a) is an east-dipping reverse fault along the eastern margin of the Yokote Basin in northern Honshu. This fault ruptured during the 1896 Rikuu earthquake and has a recurrence interval of ~3700 yr.23) The ST on the Senya segment is high (~0.98), consistent with its high activity. In contrast, the ST on the Sakunami–Yashikidaira segment (Fig. 4-b, 5-b) is low (~0.09). The Sakunami–Yashikidaira segment exhibits no evidence of faulting in the late Pleistocene and Holocene, which implies that it is not an active fault1). Consequently, the low ST on the Sakunami–Yashikidaira segment is consistent with its low seismic activity.

The difference between the calculated slip tendency for the Senya and Sakunami–Yashikidaira segments comes from the difference in dip along these fault segments. The dip of the Senya segment is 30° and the dip of the Sakunami–Yashikidaira segment is 90°, even though the strikes of these fault
segments are similar. This example highlights that the slip tendency on each fault can be derived from the characteristics of the fault (i.e., strike and dip), whereas the friction coefficient and the stress state are assumed to be constant across the region.

We now consider the overall pattern of the ST in northeastern Japan (Fig. 6). More than 80% of the active faults in northeastern Japan have ST values of >0.7. Furthermore, the ST values are related to the recurrence intervals (Fig. 7). The active faults with short recurrence intervals (<10,000 yr) have high ST values (>0.8), whereas the active faults with long recurrence intervals (>10,000 yr) have low ST values (<0.6). Yukutake et al. [2] also reported a good agreement between the average slip velocity and the calculated ST on active faults in Japan. Given that most of the faults in northeastern Japan are “active,” according to the physically based ST method, this method is effective for assessing fault activity in Japan.

However, the Haramachi segment is one of the active faults with a low ST value (Figs. 4-c, 5-c). The Haramachi segment is a N–S trending, left-lateral, strike-slip fault with west-side-up vertical displacement, and it is located along the eastern margin of the Abukuma Mountains in northern Honshu. The most recent event on the Haramachi segment fault occurred at 2200–1900 y.B.P., as determined by carbon-14 dating. [24] Therefore, the Haramachi segment appears to be an active fault, even though it has a low ST (~0.20). As such, our approach has erroneously identified this active fault as being inactive, and we now consider the reasons for this discrepancy.

4. LIMITATIONS OF THE SLIP TENDENCY METHOD

As described above for the Haramachi segment, the ST method sometimes underestimates the fault activity. Therefore, it is important to explore the cause(s) of this problem.

(1) Factors affecting the ST assessment results

The following factors can affect the ST assessment results: (1) the physical property of the fault plane (i.e., the friction coefficient); (2) the orientation of the fault plane (i.e., its strike and dip); (3) the stress field (i.e., the orientation of the principal stress and its difference ratio); and (4) other physical parameters (e.g., pore fluid pressure). These are considered in turn below.

Physical property of the fault plane (i.e., the friction coefficient): A low friction coefficient will lead to a high ST value; these potentially low shear strengths should therefore be taken into account during the ST calculations. The friction coefficient of 0.6 used in the present analysis was derived from previous laboratory experiments. [13] Sibson and Xie [25] reported that the range of friction coefficients for intracontinental reverse faults is consistent with Byerlee’s friction coefficient values (0.6–0.85). [13] However, much lower friction coefficients (0.15–0.55) have been reported from clay-rich fault gouge along the San Andreas Fault. [26] Low-friction materials (such as graphite within a fault zone) and their textural development can lower the friction on the fault. [7] As such, if the enrichment of low-friction material and its development happened on the target fault, the friction coefficient used here (0.6) might be too high to simulate fault sliding.

Orientation of the fault plane (i.e., strike and dip): The orientation of the fault plane is an important...
factor in calculating the ST. Ideally, the fault plane should not change its strike with depth. The strike of the fault at depth is assumed to be similar to the strike that we observed on fault scarps at the surface. However, fault dips change with depth, as in the case of listric normal faults that are steeply dipping near the surface and curve to lower dips with depth. This means that the fault dip we observe at the surface, which is an input for the ST calculations, can be different from the dip of the fault at depth, which should be used to calculate the ST. This mismatch between the real dip and input dip will yield an incorrect ST. Care should therefore be taken in assessing the probability of such dip changes with depth, employing geological and geophysical survey results when possible.

Stress field (i.e., orientation of the principal stress and its difference ratio): The stress inversion technique we employed has some uncertainty. However, stress difference ratios are often difficult to determine from the inversion, because stresses with similar principal directions but different stress ratios can result from the same fault activity. This kind of uncertainty in the stress state can affect the ST computation; we should therefore consider the probability of the stress state uncertainty that we estimated. Orife and Lisle proposed procedures that numerically express the difference between two stresses, termed the stress difference ($D$). They also proposed the critical values of $D$ to determine the degree of similarity for the two stresses; the two stress states are “very similar” when $D < 0.66$, with the degree of uncertainty in the stress state varying within this $D$ range.

Heterogeneity in the stress state also can affect the ST computation. For example, local anomalies in normal stress were reported after the Tohoku earthquake (11 March 2011). This suggests a regional-scale heterogeneity in the stress state in northeastern Japan. This type of stress heterogeneity has also been observed at the scale of individual fault segments. For example, Zoback et al. identified variations in the stress state along the San Andreas Fault system, and Imanishi et al. revealed a local stress anomaly in the deeper parts of the Aotsugawa Fault in Japan. As such, the homogeneous stress state that we estimated and inputted into our ST calculations may not adequately reflect the natural heterogeneous stress state. If the wrong stress state is used in the ST calculation, then the ST obtained for the fault will be inaccurate.

Other physical parameters (e.g., pore fluid pressure): It is well known that high pore fluid pressure results in enhanced fault activity. Therefore, if the pore pressure is large on a fault, then the ST method

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**Fig. 8** Variation in slip tendency with varying (a) friction of the fault surface, (b) fault dip, (c) stress difference, and (d) pore pressure as a ratio to the minimum principal stress on the fault. Red dots represent the original values of each parameter and their resultant ST values. The red solid lines in (a), (b), and (c) show possible values of fault friction, fault dip, and pore pressure, respectively, on the Haramachi segment. The blue broken lines in (a), (b), and (c) show numerically calculated but unlikely values in nature. The slip tendencies in different stress states are calculated for 168 sets of “very similar” stresses obtained in our study (Fig. 3).
may underestimate the fault activity. In this case, evaluating the pore fluid pressure is essential, although it is difficult to measure this in the crust.

(2) Magnitude of the effects of the above factors on ST

We have evaluated the magnitude of the effects of the above factors on the calculated ST values, using the Haramachi segment as a case study. We considered four factors: (1) the friction coefficient of the fault plane, (2) the dip of the fault, (3) the stress ratio and the principal stress direction, and (4) the pore fluid pressure. From a geological viewpoint, these parameters are assumed to be approximately independent of each other. We evaluated each of these parameters individually to determine the effect of each on the calculated ST values.

Friction coefficient of the fault plane: It is difficult to directly measure the friction coefficient of a fault plane, thus the exact friction coefficient of the Haramachi segment is unknown. Therefore, we varied the friction coefficient from 0.15 to 0.85, according to previous studies that reported on the range of friction coefficients on faults and/or fault materials.\(^\text{13, 26}\) and calculated the ST for each friction coefficient (Fig. 8-a). The lower limit of the friction coefficient is derived from clay-rich fault gauge (0.15),\(^\text{26}\) and the upper limit is derived from intact rocks (0.85).\(^\text{13}\) The resulting ST values range from 0.16 to 0.29. The highest ST values are obtained when the lowest friction coefficient of 0.15 is used.

Dip of the fault: The fault dip (90°) of the Haramachi segment was determined from a geological field survey.\(^\text{35}\) However, the deep geometry of the fault and basic crustal structure were investigated using deep seismic reflection profiling across the Haramachi segment of the Futaba fault, where a dip angle of 45° was obtained for the deeper part of the fault.\(^\text{34}\) The Haramachi segment is therefore thought to be a high-angle fault near the surface that evolves into a low-angle listric fault at depth. Accordingly, we calculated the ST with a range of fault dip angles (45° to 90°; Fig. 8-b) and obtained ST values from 0.20 to 0.93. The highest ST (0.93) was obtained for a moderate fault dip (~45°).

Stress ratio and principal stress direction: We varied both the stress ratio and direction of principal stress to test their effects on the uncertainty of the stress state estimated from the inversion. We prepared 60,000 sets of a random stress state,\(^\text{35}\) and selected 168 sets that exhibited “very similar” stress states to the stress we estimated (i.e., \(D < 0.66^{\text{29}}\)). When the stress difference is varied from 0 to 0.66, the ST changes from 0.01 to 0.62 (Fig. 8-c). Both the highest and lowest ST values are obtained for the high stress difference (~0.6). The ST tends to vary more as the stress difference increases, because in this case the stress ratio and the principal stress direction both cover a wider range of values.

Previous studies have examined the heterogeneity of the stress state around the Haramachi segment.\(^\text{31}\) Local strike-slip faulting stress is observed in the southern part of Sendai Bay where the Haramachi segment is located, even though reverse faulting stress in an E–W direction (E–W compressional stress) is widely observed in northeastern Japan.\(^\text{36}\) The orientation of the T-axis of the strike-slip faulting stress around the Haramachi segment is NW–SW.\(^\text{30}\) Accordingly, we calculated the ST with strike-slip faulting stress on the Haramachi segment (i.e., \(\sigma_1\) and \(\sigma_3\) orientations of 315°/0° and 225°/0° (azimuth/plunge); stress ratio = 0.5). The calculated ST is 0.96 with left-lateral, strike-slip faulting. This high ST and sense of faulting is consistent with the faulting behavior observed on the Haramachi segment.

Pore fluid pressure: We examined the effect of pore fluid pressure on the ST calculations (Fig. 8-d). We varied the pore fluid pressure from the minimum to the maximum value (\(p_f \leq p_f \leq p_f^{\text{max}}\)) (see Section 2. SLIP TENDENCY), and obtained ST values from 0.20 to 0.30. Although high pore fluid pressure significantly increases the ST value, such a pressure might not be achieved under our assumption (i.e., \(p_f \leq p_f^{\text{max}}\)).

The above considerations show that all of these factors can change the calculated ST value on the Haramachi segment. In particular, the fault dip and stress state can significantly change the ST. In the case of the Haramachi segment, high ST values that are consistent with its high fault activity are obtained when the fault dip is low and/or strike-slip faulting stress is used. Although these results can be altered for other cases, the procedure for the parameter evaluation used here is valid. This parameter evaluation is important when assessing fault activity using the ST method where direct measurements of these parameters are difficult to obtain.

5. CONCLUSIONS

We have examined the applicability of the ST method for assessing fault activity by using active fault data from northeastern Japan. High calculated ST values correspond well with active faults (e.g., the Senya segment) and the ST values are low for inactive fault (e.g., the Sakunami–Yashikidaira segments). The calculated ST values are related to the recurrence intervals. Therefore, we conclude that the
physically based ST method is a useful tool in assessing fault activity, and can potentially complement the long-term evaluation along with the chronological methods.

The ST method sometimes underestimates the fault activity, and the factors that may be responsible for this include the physical property of the fault surface (i.e., the friction coefficient), the orientation of the fault surface (i.e., strike and dip), the stress field (i.e., the orientation of the principal stress and its difference ratio), and other physical parameters (e.g., pore fluid pressure). Therefore, constraining these parameters is important in assessing fault activity using the ST method. We assessed the range of uncertainties associated with each of these parameters based on previous laboratory tests, theoretical work, and field observations. In the case of the Haramachi segment, the fault dip and stress state can significantly influence the calculated ST, and our underestimation of the activity of the Haramachi segment from the ST method might reflect these factors. Our procedure for parameter evaluation presented here is also valid for other cases. Of course, further research is required to reduce the parameter uncertainties, thereby improving the ST evaluation.

We have examined how the ST method can be used to assess fault activity based on a physical model. However, the physical mechanisms of inland earthquakes are not completely understood. The ST method used in this paper is based on a simple frictional sliding criterion controlled by friction on the fault plane in the upper crust. In contrast, Lio et al. proposed a “localized shear model,” in which seismogenic faults have downward extensions into the lower crust, and localized shear deformation on the downward extensions results in the accumulation of stress on seismogenic faults. Furthermore, our approach did not consider complex geometrical weakening and chemical strengthening, which can both affect faulting. Therefore, the assessment of fault activity using a physical model requires careful consideration of which mechanical model should be used.

When we apply this physically based method to evaluate long-term fault activity, variations in each of the parameters over geological time must be considered. Fault properties, such as friction, fault dip, and tectonic stress regimes, change over geological timescales. Our attempt to characterize the effect of these parameters in assessing fault activity should be extended in the future to estimate the effects of temporal changes in each of the parameters.

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REFERENCES
1) The research group of active faults in Japan: Active Fault in Japan, Sheet Maps and Inventories (New Edition), University of Tokyo Press, 1991 (in Japanese with English abstract).
2) Japan Nuclear Cycle Development Institute: H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan, Japan Nuclear Cycle Development Institute, 2000 (accessed 2014-04-26 from http://www.jaea.go.jp/04/tisou/english/report/H12_report.html).
3) Research Core for Deep Geological Environments, editor: Technical Report on the Review and Assessment Features, towards the Submission of the Preliminary Field Investigations of HLW Geologic Disposals. Geological Survey of Japan, AIST, Open File Report, No. 560, 2012 (accessed 2014-04-26 from https://www.gsj.jp/data/openfile/no0560/0560index.html).
4) Nuclear Regulation Authority: “Enforcement of the New Regulatory Requirements for Commercial Nuclear Power Reactors” and its attachment “New Regulatory Requirements for Light-Water Nuclear Power Plants – Outline –”, In: Authority NR, editor, 2013 (accessed 2014-04-26 from http://www.nsr.go.jp/english/e_news/data/13/0912.pdf).
5) Schwartz, D. and Coppersmith, K.: Fault behavior and characteristic earthquakes: Examples from the Wasatch and San Andreas fault zones, J. of Geophys. Res., Vol. 89, pp. 5681-5698, 1984.
6) Cooper, M. A., Williams, G. D., De Graciansky, P. C., Murphy, R. W., Needham, T., De Paor, D., Stoneley, R., Todd, S. P., Turner, J. P. and Ziegler, P. A.: Inversion tectonics—a discussion, Geological Society, London, Special Publications, Vol. 44, pp. 335-347, 1989.
7) Oohashi, K., Hirose, T. and Shimamoto, T.: Graphite as a lubricating agent in fault zones: An insight from low-to-high-velocity friction experiments on a mixed graphite-quartz gouge, J. Geophys. Res.-Solid, Vol. 118, pp. 2067-2084, 2013.
8) Miyakawa, A., Yamada, Y. and Matsuoka, T.: Effect of increased shear stress along a plate boundary fault on the formation of an out-of-sequence thrust and a break in surface slope within an accretionary wedge, based on numerical simulations, Tectonophysics, Vol. 484, pp. 127-138, 2010.
9) Yamaji, A.: The multiple inverse method applied to meso-scale faults in mid-Quaternary fore-arc sediments near the triple trench junction off central Japan, J. Struct. Geol., Vol. 22, pp. 429-440, 2000.
10) Jaeger, J. C., Cook, N. G. W. and Zimmerman, R. W. Z.: Fundamentals of Rock Mechanics, 4th ed., Wiley-Blackwell, 2007.
11) Morris, A., Ferrill, D. A. and Henderson, D. B.: Slip-tendency analysis and fault reactivation, Geology, Vol. 24, pp. 275-278, 1996.

12) Yukutake, Y., Takeda, T. and Yoshida, A.: Evaluation of active faults in the Japanese islands by using the information of stress field, Report of Research in Hot Springs Research Institute of Kanagawa Prefecture, Vol. 45, pp. 49-62, 2013 (in Japanese; accessed 2014-04-26 from http://www.onken.odawara.kanagawa.jp/files/PDF/houkoku54/houkoku54_p49-62.pdf).

13) Byerlee, J.: Friction of rocks, Pure Appl. Geophys., Vol. 116, pp. 615-626, 1978.

14) Lisle, R. J. and Srivastava, D. C.: Test of the frictional reactivation theory for faults and validity of fault-slip analysis, Geology, Vol. 32, pp. 569-572, 2004.

15) Neves, M. C., Paiva, L. T. and Luis, J.: Software for slip-tendency analysis in 3D: A plug-in for Coulomb, Comput. Geosci., Vol. 35, pp. 2345-2352, 2009.

16) Ventura, G. and Vilardo, G.: Slip tendency analysis of the Vesuvius Faults: Implications for the seismotectonic and volcanic hazard assessment, Geophys. Res. Lett., Vol. 26, pp. 3229-3232, 1999.

17) Worum, G., van Wees, J. D., Bada, G., van Balen, R. T., Cloetingh, S. and Pagnier, H.: Slip tendency analysis as a tool to constrain fault reactivation: A numerical approach applied to three-dimensional fault models in the Roer Valley rift system (southeast Netherlands), J. Geophys. Res.-Solid., Vol. 109, 2004.

18) Collettini, C. and Tripetta, F.: A slip tendency analysis to test mechanical and structural control on aftershock rupture planes, Earth Planet. Sc. Lett., Vol. 255, pp. 402-413, 2007.

19) Paola, N. D., Collettini, C., Tripetta, F., Barchi, M. R. and Minelli, G.: A mechanical model for complex fault patterns induced by evaporite dehydration and cyclic changes in fluid pressure, J. Struct. Geol., Vol. 29, pp. 1573-1584, 2007.

20) Leclère, H. and Fabbri, O.: A new three-dimensional method of fault reactivation analysis, J. Struct. Geol., Vol. 48, pp. 153-161, 2013.

21) Yoshida, K., Hasegawa, A., Okada, T., Inuma, T., Ito, Y. and Asano, Y.: Stress before and after the 2011 great Tohoku-oki earthquake and induced earthquakes in inland areas of eastern Japan, Geophys. Res. Lett., Vol. 39, L03302, 2012.

22) Otsubo, M., Yamaji, A. and Kubo, A.: Determination of stresses from heterogeneous focal mechanism data: An adaptation of the multiple inverse method, Tectonophysics, Vol. 457, pp. 150-160, 2008.

23) Matsuda, T., Yamazaki, H., Nakata, T. and Imaizumi, T.: The surface faults associated with the Rikuu Earthquake of 1896, Bulletin of the Earthquake Research Institute, University of Tokyo, Vol. 55, pp. 795-855, 1980 (in Japanese with English abstract).

24) Fukushima. Report on Futaba fault. Result Report for Seismic Investigation Research Subsidy in the 1997 Fiscal Year. 1998 (in Japanese; accessed 2014-04-26 from http://www.hp1039.jishin.go.jp/danso/Fukushima4frm.hm).

25) Sibson, R. H. and Xie, G.: Dip range for intracontinental reverse fault ruptures: Truth not stranger than friction?, B. Seismol. Soc. Am., Vol. 88, pp. 1014-1022, 1998.

26) Morrow, C., Radney, B. and Byerlee, J.: Frictional strength and the effective pressure law of montmorillonite and illite clays, Int. Geophys., Vol. 51, pp. 69-88, 1992.

27) Twiss, R. J. and Moores, E. M.: Structural Geology, 2nd ed., New York, W. H. Freeman, 2007.

28) Yamaji, A.: The multiple inverse method: A new technique to separate stresses from heterogeneous fault-slip data, J. Struct. Geol., Vol. 22, pp. 441-452, 2000.

29) Orife, T. and Lisle, R. J.: Numerical processing of palaeostress results, J. Struct. Geol., Vol. 25, pp. 949-957, 2003.

30) Zoback, M. D., Zoback, M. L., Mount, V. S., Suppe, J., Eaton, J. P., Healy, J. H., Oppenheimer, D., Reasenberg, P., Jones, L., Raleigh, C. B., Wong, I. G., Scotti, O. and Wentworth, C.: New evidence on the stress state of the San Andreas fault system, Science, Vol. 238, pp. 1105-1111, 1987.

31) Imanishi, K., Kuwahara, Y., Takeda, T., Mizuno, T., Ito, H., Ito, K., Wada, H. and Haryu, Y.: Depth-dependent stress field in and around the Aotsugawa fault, central Japan, deduced from microearthquake focal mechanisms: Evidence for localized aseismic deformation in the downward extension of the fault, J. of Geophys. Res.-Solid, Vol. 116, B01305, 2011.

32) Sibson, R. H.: Fault-valve behavior and the hydrostatic-lithostatic fluid pressure interface, Earth-Sci. Rev., Vol. 32, pp. 141-144, 1992.

33) Yanagisawa, Y., Yamamoto, T., Banno, Y., Tazawa, J., Yoshioka, T., Kubo, K. and Takizawa, F.: Geology of Sōmanakamura district. With Geological Sheet Map at 1:50,000, Geological Survey of Japan, AIST, p. 144, 1996 (in Japanese, with English abstract).

34) Sato, H., Ishiyama, T., Kato, N., Higashinaka, M., Kurashimo, E., Iwasaki, T. and Abe, S.: An active footwall shortcut thrust revealed by seismic reflection profiling: a case study of the Futaba fault, northern Honshu, Japan, EGU General Assembly Geophys. Res. Abstr., Vol. 15, EGU2013-8871-1, 2013.

35) Yamaji, A. and Sato, K.: A spherical code and stress tensor inversion, Comput. Geosci., Vol. 38, pp. 164-167, 2012.

36) Terakawa, T. and Matsu‘Ura, M.: The 3-D tectonic stress fields in and around Japan inverted from centroid moment tensor data of seismic events, Tectonics, Vol. 29, TC6008, 2010.

37) Iio, Y. and Kobayashi, Y.: A physical understanding of large intraplate earthquakes, Earth Planets Space, Vol. 54, pp. 1001-1004, 2002.

38) Niemeijer, A., Marone, C. and Elseworth, D.: Frictional strength and strain weakening in simulated fault gouge: Competition between geometrical weakening and chemical strengthening, J. Geophys. Res.-Solid, Vol. 115, B10207, 2010.

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