TITLE:

Stability of the regional stress field in central Japan during the late Quaternary inferred from the stress inversion of the active fault data

AUTHOR(S):

Tsutsumi, Hiroyuki; Sato, Katsushi; Yamaji, Atsushi

CITATION:

Tsutsumi, Hiroyuki ...[et al]. Stability of the regional stress field in central Japan during the late Quaternary inferred from the stress inversion of the active fault data. Geophysical Research Letters 2012, 39(23): L23303.

ISSUE DATE:

2012-12

URL:

<http://hdl.handle.net/2433/167965>

RIGHT:

©2012. American Geophysical Union.; This is not the published version. Please cite only the published version.; この論文は出版社版ではありません。引用の際には出版社版をご確認ご利用ください。

- 1 **Stability of the regional stress field in central Japan during the late Quaternary**
- 2 **inferred from the stress inversion of the active fault data**
- 3
- 4 **Hiroyuki Tsutsumi¹, Katsushi Sato¹, and Atsushi Yamaji¹**
- 5 ¹Division of Earth and Planetary Science, Graduate School of Science, Kyoto University,
- 6 Kyoto 606-8502, Japan

7 ABSTRACT

8 We analyzed 169 geological fault-slip data from 37 active faults in central Japan to
9 investigate the late Quaternary stress field stability. Modern stress states have been
10 documented with unprecedented accuracy; however, their stability over time scales
11 beyond instrumental observations is inadequately understood. Because the stress field
12 has changed in the geological past, we compared present stress conditions in central
13 Japan, determined from geophysical observations, with conditions determined by
14 inverting the fault-slip data from active faults that exhibited cumulative displacement
15 for the past $\sim 10^5$ years. The maximum stress axis obtained from fault-slip data trends
16 ESE–WNW. This state of stress accounts for 97% of the data and supports the fact that
17 oblique faults with reverse and strike-slip senses are interlaced in the region. The
18 optimal stress is similar to the present stress state, indicating that the stress field in
19 central Japan has been uniform and stable over the past $\sim 10^5$ years.

20

21 1. Introduction

22 The crustal stress field is one of the most important parameters required to
23 understand tectonics, but the secular variation or stability of tectonic stress is not
24 adequately understood for the time scales of 10^3 – 10^5 years. The World Stress Map
25 (WSM) Project was the first coordinated effort to map tectonic stress fields worldwide
26 [Zoback, 1992], and the WSM database released in 2008 [Heidbach *et al.*, 2010]
27 contains three times as much stress data as that of the 1992 database. Most of the data
28 sets used to derive the stress fields in the project are geophysical data such as those
29 derived from the focal-mechanism solutions of earthquakes and wellbore breakout. In
30 contrast, geological data such as fault-slip data and volcanic-vent alignment accounted

for only ~10% of the total data [Zoback, 1992; Heidbach *et al.*, 2010]. The geophysical data reveal stress fields on the time scales of 10^0 – 10^2 years, whereas the geological data reveal stress fields over longer periods, usually 10^5 years or longer. Active faults are the clues that will help in filling the gap between the time scales of geophysical and geological observations because their intermittent but steadily growing displacements over the last 10^3 – 10^5 years are evident from, e.g., geomorphology, paleoseismic trenching, and seismic-reflection profiling. Central Japan is suitable for crustal stress-field analyses on different time scales because it contains one of the world's highest-quality geophysical [e.g., Mazzotti *et al.*, 2001; Townend and Zoback, 2006; Terakawa and Matsu'ura, 2010] and geological [e.g., *The Research Group for Active Faults of Japan*, 1991; Nakata and Imaizumi, 2002] data sets.

Permanent regional strain in central Japan has been accommodated mainly by active faults, which form a dense network in the region [*The Research Group for Active Faults of Japan*, 1991; Nakata and Imaizumi, 2002] (Figure 1). Since the 1995 Kobe earthquake, most of the long and fast-slipping faults in the region have been studied extensively through a national active-fault research program, which has produced one of the most comprehensive active-fault data sets in the world. Therefore, non-Andersonian faults have gradually become clear; reverse and strike-slip faults are interlaced in this region. In addition, a few of these types of faults have trends subparallel to each other while exhibiting different dip angles: the Hanaore and Biwako-seigan faults represent such a pair and are interpreted as an example of strain partitioning (Figure 1). Active faulting and its relation to the stress field in central Japan have been a topic of debate [Huzita, 1968; Okada and Ando, 1979], but the coexistence of faults with different senses of motion makes inference difficult without the inclusion of a special type of

55 stress-tensor inversion, as described below.

56 Stress-tensor inversion is used to determine stress conditions from the fault-slip data.
57 Each datum comprises the attitude of a fault and the slip direction on the fault plane
58 [e.g., *Angelier*, 1979] (Figure 2a). However, the slip directions are seldom determined
59 along the segments of active faults. Instead, the directions are vaguely documented in
60 the terms of slip senses. For example, the slip direction of a reverse fault has an
61 uncertainty of 180° with respect to the rake direction; the dip occurs at the center of
62 possible slip directions for the footwall block (Figure 2b). Similarly, the slip direction of
63 a strike-slip fault has an uncertainty of 180°, but the possible slip direction is horizontal
64 from the center of the slip. A few active faults in central Japan are described as oblique
65 reverse faults with sinistral or dextral components. The slip directions of these faults
66 have an uncertainty of 90° (Figure 2c). A fault-slip data set for active faults in central
67 Japan includes such deficiencies. *Lisle et al.* [2001] developed a pioneering
68 stress-inversion method to deal with sense-only data. Recently, *Sato* [2006] developed a
69 special type of stress-inversion method to deal with mixed set of complete and
70 sense-only fault-slip data.

71 In this study, we apply *Sato's* [2006] method to the active fault data to derive the
72 regional stress field in central Japan. Although the slip inversion of a single active fault
73 was conducted by *Blenkinsop* [2006] for the Chelungpu fault that ruptured during the
74 1999 Chi-Chi earthquake in Taiwan, this is the first study to reveal a regional stress field
75 based on the stress inversion analysis of a large set of the active fault data. We show that
76 central Japan is under an ESE–WNW compressional stress field with a small stress ratio,
77 $\Phi = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$, and that the regional stress field has been uniform and stable
78 over the past $\sim 10^5$ years.

79

80 2. Tectonic setting

81 To the east of the Japanese islands, the Pacific plate is subducted westward beneath
82 the North American and Philippine Sea plates (Figure 1). Along the Nankai trough, the
83 Philippine Sea plate has been subducting northwestward since the Pliocene or
84 mid-Pleistocene [e.g., *Seno and Maruyama*, 1984; *Yamaji*, 2000]. In the study area, i.e.,
85 the eastern part of the southwest Japan arc, north-trending reverse faults and
86 northwest-trending left-lateral and northeast-trending right-lateral strike-slip faults are
87 densely distributed (Figure 1). The offsets of dated geomorphic features indicate slip
88 rates in the order of 10^{-1} to 10^0 mm/yr for such faults [*The Research Group for Active*
89 *Faults of Japan*, 1991]. Central Japan has a long historical earthquake record that has
90 been systematically collected for several centuries [*Usami*, 2003; *Ishibashi*, 2004]. The
91 area has experienced one reverse-slip and four strike-slip earthquakes that ruptured the
92 surface since the 1891 Nobi earthquake (Figure 1).

93 Geodetic and seismological data show that the Japan arc is subject to an
94 approximate E–W compression. *Mazzotti et al.* [2001] calculated the permanent
95 deformation field in central Japan by subtracting short-term elastic deformation related
96 to the locking of the plate interface along the Nankai trough from GPS observations,
97 and they obtained the residual-deformation field indicating ESE–WNW shortening.
98 *Townend and Zoback* [2006] reported that the maximum horizontal stress is oriented
99 approximately toward ENE–WSW in southwest Japan. *Terakawa and Matsu'ura* [2010]
100 used the centroid-moment-tensor data to show that the tectonic stress of the Japan arc is
101 basically an E–W compression with the direction of intermediate principal stress
102 changing from N–S in northeast Japan to vertical in southwest Japan.

103

104 3. Data

105 After the 1995 Kobe earthquake, the Headquarters for Earthquake Research
106 Promotion (HERP) of the Japanese government selected approximately 100 inland
107 active faults and conducted extensive geological and paleoseismological studies to
108 assess their seismic potential. We compiled the fault-slip data from 36 active faults
109 selected by HERP in the Chubu and Kinki districts, to the west of the
110 Itoigawa–Shizuoka tectonic line and east of the Nojima fault that ruptured during the
111 1995 Kobe earthquake (Figure 1). To exclude local-stress perturbation due to the
112 collision of the Izu Peninsula with the main island of Japan [e.g., *Mazzotti et al.*, 2001;
113 *Townend and Zoback*, 2006] from our regional stress analysis, we analyzed the data for
114 the faults to the west of the Itoigawa–Shizuoka tectonic line, which is part of the
115 postulated plate boundary between the North American and Eurasian plates [*Nakamura*,
116 1983]. We examined data from paleoseismic trench walls, natural outcrops, and seismic
117 reflection profiles in published reports and maps. To determine the stress regime for a
118 time scale of 10^5 years, we compiled the data on faults that clearly offset geomorphic
119 surfaces or strata of late Quaternary age dated by tephrochronology or radiometric
120 methods. Therefore, we catalogued reliable fault orientations and slip senses at 166 sites
121 along 36 faults (Table S1 in the auxiliary material). In addition, we catalogued the data
122 from three sites along the Fukozu fault, the source fault of the 1945 Mikawa earthquake
123 that was not selected by HERP but for which extensive paleoseismic trenching was
124 conducted [e.g., *Sone and Ueta*, 1993].

125 The fault-slip data set used in this study had a few deficiencies. Slickenlines were
126 observed to determine the rakes of slip vectors at only 11 sites out of 169. We obtained

the “complete” data for 11 sites, and the remaining sites produced “sense-only” data, which have the rake uncertainties of 90° or 180° (Figures 2b and c). Figures 2d–f illustrate the tangent-lineation diagrams [Twiss and Gefell, 1990], improved by Sato [2006], that display the fault attitude and possible slip directions of the complete and sense-only data. A complete datum is denoted by an arrow plotted by a lower-hemisphere, equal-area projection; the pole of the fault plane is depicted in the stereogram by the position of the arrow, which itself indicates the slip direction of the footwall block (Figure 2d). The inward and outward directions of the arrow indicate the reverse and normal senses of shear, respectively. Strike-slip faults are represented by such arrows that are directed perpendicular to the radial directions in the plot. A sense-only datum is denoted by a semicircle or fan, which indicates the possible slip direction of the footwall block (Figures 2e and f). Figure 3 shows the fault-slip data from the active faults in the study area; we recorded a large variation of fault attitudes from 169 sites distributed along 37 faults.

4. Stress inversion

The stress-inversion method proposed by Sato [2006] was employed to determine the stress conditions that explain the mixed set of the complete and sense-only data. The method can deal with both the complete and sense-only data by placing tighter and looser constraints on the conditions, respectively. The Wallace–Bott hypothesis is assumed, as is customary: the slip directions of faults are assumed to be parallel to the resolved shear stresses (theoretical slip directions) on the fault planes, which are calculated from the fault attitudes and stress conditions. The fitness of arbitrary stress conditions to a datum, i.e., how preferable is the assumption for a fault, is defined as a

decreasing function of the misfit angle d between the theoretical and observed slip directions (Figure 2g). The threshold in the function d_T is set to 30° in this study. For the sense-only data, the misfit angles are measured from the center of possible slip directions, and the degrees of fit are equal within the possible range (Figures 2h and i). According to *Sato* [2006], all the types of fitness functions are normalized as probability-density functions in the parameter space of deviatoric stress, which is represented schematically as the heights of fitness values in Figures 2g–i. The degrees of fit are added over the entire set of the complete and sense-only data to provide a total fitness of stress conditions. The optimal stress conditions are searched to maximize the total fitness. Although the complete data are uncommon in our database (Figure 3 and Table S1), the large variation of fault orientations and large number of data enable us to obtain a stress state with a relatively high precision.

Figure 4 shows the optimal stress for our data. A reverse-faulting stress-regime with an ESE–WNW-trending σ_1 -axis was found to be capable of explaining almost all the data. The stress ratio, $\Phi = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$, was determined to be 0.09, which means that the magnitude of σ_2 is approximately equal to that of σ_3 . In addition, Figure 4 illustrates the uncertainty of the solution by plotting principal stress axes that have fitness values greater than 90% of those of the optimal solution. Because of the small Φ value (axial compressional stress), the σ_3 -axis has a greater uncertainty than that of the σ_1 -axis. We calculated theoretical slip directions for the faults by assuming optimal stress; white arrows in Figure 5 denote these directions.

5. Discussion

Despite the large variation of fault orientations (Figures 1 and 3), stress inversion revealed that almost all the active faults in the study area are consistent with a reverse-faulting stress regime with ESE–WNW-trending σ_1 -axis (Figure 5). The theoretical slip directions of the faults calculated with this optimal stress were consistent with all the data except for five of them. Some of these exceptions have fault planes nearly perpendicular to the optimal σ_1 -axis. Theoretical slip directions on such fault planes are unstable as is shown by the radial pattern around the σ_1 -axis in Figure 5. Therefore, small perturbations in fault attitudes can explain the large misfits.

The optimal stress ratio of 0.09 indicates that σ_2 and σ_3 have similar values. Such a state of stress allows the coexistence of reverse and strike-slip faults, provided that they have different fault orientations. Their coexistence puzzled previous researchers who inferred the stress field from active faults in Japan because they assumed Andersonian faulting [Huzita, 1968; Okada and Ando, 1979]. Consequently, they neglected the coexistence of reverse and strike-slip faults or they had to infer spatially or temporarily complicated stress fields.

Although the ESE–WNW compression determined from active faults in this study is generally the same as that proposed by Huzita [1968], we demonstrated that a single state of stress explains the fault-slip data from all sites except five of them. This means that the stress field in central Japan has been uniform and that the active faults have slipped in the same directions over the past $\sim 10^5$ years. From the coexistence of reverse and strike-slip faults, we predicted that non-Andersonian, oblique-slip faulting is common in this region although the rakes of slip vectors were observed for only 10 of 37 faults.

The reactivation of the pre-existing planes of weakness gives rise to the

non-Andersonian faulting of planes with a wide variety of orientations. *Kano* [2002] suggested that a few active faults are present in such planes in the Mesozoic accretionary complex in the northern part of the study area. For example, the left-lateral Yanagase fault (Figure 1) reactivated a kink plane of a map-scale chevron fold. Similarly, the right-lateral Hanaore fault (Figure 1) lies along the axial surface of a fold structure [*Kano*, 2002]. *Ito* [2006] obtained the apatite fission track ages of ~20 Ma for dikes intruded along the Yanagase fault, which provides a minimum age constraint for the fault. *Murakami and Tagami* [2004] conducted the zircon fission-track analysis of pseudotachylyte sampled from the Nojima fault (Figure 1). They suggested that the Nojima fault was already initiated at ~56 Ma. The active Median Tectonic Line (Figure 1) follows part of the boundary between the Ryoke and Sanbagawa terranes that were accreted in the Mesozoic [*Hashimoto*, 1991]. Therefore, a few active faults in central Japan reactivated the pre-existing faults under the present-day stress regime.

Slip on the active faults catalogued in this study reflects the average stress regime in the late Quaternary. The inverted stress state determined in this study is principally consistent with that obtained by geodetic and seismological data [*Mazzotti et al.*, 2001; *Townend and Zoback*, 2006; *Terakawa and Matsu'ura*, 2010], suggesting that the stress state in central Japan has been uniform and stable for the past $\sim 10^5$ years.

6. Conclusions

A dense distribution and an extensive data set of active faults in central Japan has provided us with an exceptional opportunity to invert the regional stress field over a time scale of $\sim 10^5$ years. We obtained an optimal state of stress, which is essentially the same as that obtained by seismological and geodetic data, indicating that the stress field

222 in the eastern part of southwest Japan has been stable over the past $\sim 10^5$ years.
223 Moreover, the inversion results provide a clear explanation for the coexistence of
224 reverse and strike-slip faults in central Japan. Geological observations suggest that a
225 few active faults in central Japan reactivated pre-existing faults under the present-day
226 stress regime.

227

228 **Acknowledgments**

229 We thank Ritsuko Matsu'ura at the Association for the Development of Earthquake
230 Prediction for access to the literature on the active faults used in this study and Shigeru
231 Sueoka for his assistance in compiling the active fault database. We are grateful to
232 Richard Lisle and Robert Yeats for constructive reviews.

233

234 **References**

- 235 Angelier, J. (1979), Determination of the mean principal directions of stresses for a
236 given fault population, *Tectonophysics*, 56, T17-T26.
- 237 Blenkinsop, T. G. (2006), Kinematic and dynamic fault slip analyses: implications from
238 the surface rupture of the 1999 Chi-Chi, Taiwan, earthquake, *J. Struct. Geol.*, 28,
239 1040-1050.
- 240 Hashimoto, M. (Ed.) (1991), *Geology of Japan*, Terra Scientific Publishing Company,
241 Tokyo.
- 242 Heidbach, O, M. Tingay, A. Barth, J. Reinecker, D. Kurfeß, and B. Müller (2010),
243 Global crustal stress pattern based on the World Stress Map database release 2008,
244 *Tectonophysics*, 428, 3-15.
- 245 Huzita, K. (1968), Rokko movements and its appearance: intersecting structural patterns

- 246 of southwest Japan and Quaternary crustal movements, *Quaternary Res.*, 7, 248-260.
- 247 (in Japanese with English abstract)
- 248 Ishibashi, K. (2004), Status of historical seismology in Japan, *Ann. Geophys.*, 47,
- 249 339-368.
- 250 Ito, H. (2006), Early Miocene igneous activity around northern part of the Yanagase
- 251 fault and constraints on its fault activity from fission-track thermochronology, *J. Geol.*
- 252 *Soc. Japan*, 112, 612-615. (in Japanese with English abstract)
- 253 Kano, K. (2002), Steeply-plunging, map-scale folds in the Mino-Tanba Belt, Southwest
- 254 Japan: origin of the Yanagase Fault as viewed from the basement structures, *J. Geol.*
- 255 *Soc. Japan*, 108, 591-605. (in Japanese with English abstract)
- 256 Kikuchi, M., and H. Kanamori (1996), Rupture process of the Kobe, Japan, earthquake
- 257 of Jan. 17, 1995, determined from teleseismic body waves, *J. Phys. Earth*, 44,
- 258 429-436.
- 259 Lisle, R., T. Orife, and L. Arlegui (2001), A stress inversion method requiring only slip
- 260 sense, *J. Geophys. Res.*, 106, 2281-2289.
- 261 Mazzotti, S., P. Henry, and X. Le Pichon (2001), Transient and permanent deformation
- 262 of central Japan estimated by GPS: 2. Strain partition and arc-arc collision, *Earth*
- 263 *Planet. Sci. Lett.*, 184, 455-469.
- 264 Murakami, M., and T. Tagami (2004), Dating pseudotachylyte of the Nojima fault using
- 265 the zircon fission-track method, *J. Geophys. Res.*, 31, L12604,
- 266 doi:10.1029/2004GL020211.
- 267 Nakamura, K. (1983), Possible nascent trench along the eastern Japan Sea as the
- 268 convergent boundary between Eurasian and North American plates, *Bull. Earthq. Res.*
- 269 *Inst. Univ. Tokyo*, 58, 711-722. (in Japanese with English abstract)

- 270 Nakata, T., and T. Imaizumi (Eds.) (2002), *Digital Active Fault Map of Japan*,
271 University of Tokyo Press, Tokyo. (in Japanese)
- 272 Okada, A., and M. Ando (1979), Active faults and earthquakes in Japan, *Kagaku*, 49,
273 158-169. (in Japanese)
- 274 Sato, K. (2006), Incorporation of incomplete fault-slip data into stress tensor inversion,
275 *Tectonophysics*, 421, 319-330.
- 276 Seno, T., and S. Maruyama (1984), Paleogeographic reconstruction and origin of the
277 Philippine Sea, *Tectonophysics*, 102, 53-84.
- 278 Shiono, K. (1977), Focal mechanisms of major earthquakes in southwest Japan and
279 their tectonic significance, *J. Phys. Earth*, 25, 1-26.
- 280 Sone, K., and K. Ueta (1993), Trenching study of the Fukozu fault at Tokoji, Aichi
281 Prefecture in 1988, *Active Fault Res.*, 11, 43-46. (in Japanese)
- 282 Terakawa, T., and M. Matsu'ura (2010), The 3-D tectonic stress fields in and around
283 Japan inverted from centroid moment tensor data of seismic events, *Tectonics*, 29,
284 TC6008, doi: 10.1029/2009TC002626.
- 285 The Research Group for Active Faults of Japan (Ed.) (1991), *Active Faults in Japan:*
286 *Sheet Maps and Inventories (revised edition)*, University of Tokyo Press, Tokyo. (in
287 Japanese with English abstract)
- 288 Townend, J., and M. D. Zoback (2006), Stress, strain, and mountain building in central
289 Japan, *J. Geophys. Res.*, 111, B03411, doi: 10.1029/2005JB003759.
- 290 Twiss, R. J., and M. J. Gefell (1990), Curved slickenfibers - a new brittle shear sense
291 indicator with application to a sheared serpentinite, *J. Struct. Geol.*, 12, 471-481.
- 292 Usami, T. (2003), *Materials for Comprehensive List of Destructive Earthquakes in*
293 *Japan (latest edition)*, University of Tokyo Press, Tokyo. (in Japanese)

294 Yamaji, A. (2000), The multiple inverse method applied to meso-scale faults in
295 mid-Quaternary fore-arc sediments near the triple junction off central Japan, *J. Struct.*
296 *Geol.*, 22, 429-440.
297 Zoback, M. L. (1992), First- and second-order patterns of stress in the lithosphere: the
298 World Stress Map project, *J. Geophys. Res.*, 97, 10703-11728.

299

300 **Figure captions**

301 Figure 1. Tectonic setting and distribution of active faults in the Kinki and Chubu
302 districts of central Japan. The active fault traces (red lines) are from *Nakata and*
303 *Imaizumi* [2002], and black arrows denote major strike-slip faults. Blue crosses
304 denote the locations of outcrops, trench sites, and seismic-reflection profiles from
305 where the fault-slip data were collected. Focal-mechanism solutions for historical
306 surface-rupturing earthquakes are also shown by *Shiono* [1977] and *Kikuchi and*
307 *Kanamori* [1996]: 1891 Nobi, 1927 Kita-Tango, 1945 Mikawa, 1948 Fukui, and
308 1995 Kobe earthquakes. Active faults mentioned in the text are Biwako-seigan
309 fault: BF, Fukozu fault: FF, Hanaore fault: HF, Median Tectonic Line: MTL,
310 Nojima fault: NF, and Yanagase fault: YF. Other abbreviations are
311 Itoigawa-Shizuoka tectonic line: ISTL, Kyoto: Ky, Nagoya: Na, Osaka: O. Inset
312 shows the plate-tectonic setting of Japanese islands. Eurasian plate: EU, Izu
313 Peninsula: IP, North American plate: NA, Pacific plate: PA, Philippine Sea plate:
314 PH. Thick arrows denote convergence directions between the Pacific and North
315 American plates and between the Philippine Sea and Eurasian plates.

316

317 Figure 2. Types of fault-slip data and their constraints on stress condition. Figure (a)

shows a complete fault-slip datum comprising the attitude and slip direction of the fault. The direction is indicated by slickenlines on the fault plane. Figures (b) and (c) show the “sense-only” data obtained from faults on which slickenlines are not observed but whose sense of faulting is known from, for example, fault scarps and stream offsets. Either strike-slip sense or dip-slip sense of shear is known in (b), and both are known in (c). The possible slip directions of the footwalls are constrained within the range indicated by the semicircle and quadrant drawn on the fault plane. Figures (d–f) show the fault-slip data expressed in tangent-lineation diagrams [Twiss and Gefell, 1990] improved by Sato [2006]. Panels (d), (e), and (f) correspond to (a), (b), and (c), respectively. Figures (g–i) are graphs showing the fitness functions (bold lines) used in stress inversion, which can deal with all the types of the fault-slip data to determine the state of stress responsible for the observed fault movements. Figure (g) shows a fault with the complete data and the misfit angle d is between the theoretical and observed slip directions. Figures (h) and (i) show the case of a sense-only datum and d is defined as the angle formed by the theoretical slip direction and the central line of the semicircle or the fan.

Figure 3. Tangent-lineation diagram of the complete and sense-only fault-slip data obtained from the active faults in the study area. See Figure 2 for the explanations of the symbols.

Figure 4. Paired stereograms showing the range of stress conditions admissible for the fault-slip data in Figure 3. The stress ratios and principal orientations of the conditions are indicated by rainbow colors and lower-hemisphere, equal-area

342 projections. Stars denote the optimal orientations. The small circles are the
343 principal axes of stresses with fitness greater than 90% of that of the optimal
344 solution.

345

346 Figure 5. Optimal stress axes (open stars) and calculated theoretical slip directions
347 (white arrows) plotted on a tangent-lineation diagram with a lower-hemisphere,
348 equal-area projection. The fault-slip data are the same as that in Figure 3. The
349 fault-slip data shown in red are inconsistent with the theoretical slip directions.
350 Note that most of the data agree with the theoretical slip directions.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Fault-slip data

with small misfit

with large misfit

Complete data

Sense-only data

→ Theoretical slip direction for optimal stress condition

Figure 5.

Table S1 Fault-slip data from 37 active faults in central Japan

Fault name (50 numbers)	Name	Fault-slip data (Site No.)	Site source	Latitude (°N)	Longitude (°E)	Strike	Dip	Sense of slip	Rate of slip (vector)	Age of faulting(1)	Inversion analysis	Remarks	Dip direction(2)	Slip orientation(3)	
45	Etsu-noyama-shan	45-1	natural outcrop	35.346	137.5839	N02	85W	right-lateral		Holocene	1		275	85	
		45-2	natural outcrop	35.6534	137.6865	N04E	100	right-lateral		in the past 2000 years	1		144	55	
		45-3	treaching	35.7206	137.7247	N02E	100-106	reverse, right-lateral		in the past 2000 years	1		180	46	
		45-4	treaching	35.7824	137.7124	N20E	20E	reverse, right-lateral		Holocene	1		115	29	
46	Saitohage-Kamiji	46-1	treaching	35.9421	137.7811	N20W	03E (north well)	left-lateral		in the past 2000 years	1		79	65	
		46-2	natural outcrop	36.8622	137.780	N08W	88W-vertical	left-lateral		Holocene	1		239	85	
		46-3	treaching	36.8335	137.7869	N20W	78E-vertical	left-lateral		Holocene	1		79	88	
		46-4	treaching	35.7886	137.7348	N20E	40E-48E	left-lateral		Holocene	1		62	58	
		46-5	natural outcrop	36.8779	137.8668	N08W	78E	left-lateral		Late Pleistocene	0.5	close to 46-2	72	79	
		46-6	natural outcrop	36.8773	137.6863	N08W	78E	left-lateral		Late Pleistocene	0.5	close to 46-5	38	58	
		46-7	natural outcrop	36.8356	137.7315	N24W	78E	left-lateral		20N	Holocene	1		76	79
47	Atsugawa	47-1	treaching	36.3275	137.1376	N46E	45-75W	right-lateral		12W	historical (1893)	1		138	79
		47-2	natural outcrop	36.3218	137.5884	N02E	80E	right-lateral		20-30N	historical (1893)	1		145	88
		47-3	treaching	36.4521	137.1443	N02E	vertical	right-lateral		historical (1893)	1		335	90	
		47-4	natural outcrop	36.4246	137.1511	N02E	80W	right-lateral		historical (1893)	1		313	88	
48	Tatsugawa-Oppara	48-1	treaching	36.3479	137.1235	N46E	75E-85E	right-lateral			Holocene	1		138	79
		48-2	treaching	36.1372	137.1041	N70E	50-80E	right-lateral			Holocene	1		138	65
		48-3	treaching	36.0466	137.1246	N02E	88W-vertical	right-lateral			Holocene	0.5	close to 48-4	315	88
		48-4	treaching	36.0463	137.1261	N02E	72W	right-lateral			Holocene	0.5	close to 48-3	365	77
		48-5	treaching	36.8278	137.1271	N08E	vertical	right-lateral			Holocene	1		129	90
		48-6	natural outcrop	36.8749	137.1882	N02E	78E	right-lateral			Late Pleistocene	1		123	79
49	Ishikubi	49-1	natural outcrop	36.2971	136.9453	N46E	78E	right-lateral			Late Pleistocene	1		128	79
		49-2	natural outcrop	36.3841	136.9613	N08E	48E	right-lateral			Holocene	1		129	48
		49-3	treaching	36.3841	136.7902	N02E	vertical	right-lateral		in the past 2000 years	0.5	close to 49-4	325	90	
		49-4	treaching	36.3839	136.5986	N02E	vertical	right-lateral		in the past 2000 years	0.5	close to 49-3	325	90	
		49-5	treaching	36.3227	137.6866	N02E	88E-78W	right-lateral		in the past 2000 years	1		325	65	
		49-6	treaching	36.4873	137.1135	N02E	vertical	right-lateral		in the past 2000 years	1		315	90	
50	Shikawa	50-1	natural outcrop	36.3294	136.8429	N08W	vertical	left-lateral			Late Pleistocene	1		68	90
		50-2	treaching	36.3389	136.8893	N08W	48-48W	left-lateral			Holocene	1		268	58
51	Inabiri	51-1	treaching	35.9871	137.8546	N20W	78E	left-lateral			historical (1585)	1		79	79
		51-2	setatic profiling	35.8551	137.8476	N08W	80E	reverse			Late Pleistocene	1		269	85
		51-3	setatic profiling	35.8521	137.8512	N08W	20-30W	reverse			Late Pleistocene	1		270	25
		51-4	treaching	35.8521	137.8686	N08W	25-35W	reverse			Late Pleistocene	1		268	48
		51-5	treaching	35.7825	137.8553	N08W	80E	reverse			historical (1586 or 1718)	1		268	58
52	Awa	52-1	natural outcrop	35.897	137.1385	N48	vertical	left-lateral			Late Pleistocene	1		84	90
		52-2	natural outcrop	35.8885	137.1389	N23W	88E	left-lateral		25-34E	Late Pleistocene	1		69	88
		52-3	natural outcrop	35.7483	137.1207	N08W	72W	left-lateral			historical (1586)	1		271	73
		52-4	treaching	35.7897	137.2952	N08W	88W	left-lateral			historical (1586)	0.5	close to 52-5	45	88
		52-5	treaching	35.7881	137.2862	N08W	88W	left-lateral			historical (1586)	0.5	close to 52-4	45	88
		52-6	natural outcrop	35.7676	137.1227	N7E	82E	left-lateral			Late Pleistocene	1		83	87
		52-7	treaching	35.7351	137.1238	N48E	vertical	left-lateral			in the past 2000 years	1		83	87
		52-8	treaching	35.7436	137.1486	N08W	73W	left-lateral			Holocene	1		45	75
		52-9	treaching	35.6217	137.1317	N08W	vertical	left-lateral			Holocene	1		45	75
		52-10	natural outcrop	35.6125	137.1487	N08W	88W	left-lateral			Holocene	1		45	75
		52-11	treaching	35.5715	137.1458	N08W	88W	left-lateral			Holocene	1		45	75
		52-12	treaching	35.5336	137.1606	N08W	88W	left-lateral			Holocene	0.5	close to 52-13	228	88
53	Ryugasaki-Etsu	53-1	treaching	35.3689	137.4524	N45E	50-58E	reverse, right-lateral			Holocene	1		148	48
		53-2	treaching, borehole survey	35.2273	137.1831	N48E	80E	right-lateral			Holocene	1		138	88
54	Sagayama	54-1	treaching, borehole survey	34.8825	136.9541	N20W	88W	reverse			Late Pleistocene	1		230	88
		54-2	setatic profiling	34.8825	136.9541	N20W	88W	reverse			Late Pleistocene	1		230	88
55	Dokugata	55-1	setatic profiling	36.5626	136.8867	N08E	28E	reverse			Late Pleistocene	0.5	close to 55-2	138	28
		55-2	treaching	36.5623	136.8866	N08E	28E	reverse			in the past 2000 years	0.5	close to 55-1	138	28
56	Tomahiyae-Kumohyama	56-1	setatic profiling	36.3633	136.8541	N02E	45-50W	reverse			Late Pleistocene	1		315	47.5
		56-2	setatic profiling	36.3633	136.8541	N02E	45-50W	reverse			Late Pleistocene	1		315	47.5
		56-3	treaching	36.3605	136.5483	N02E	40E	reverse			Holocene	1		128	28
		56-4	setatic profiling	36.6215	137.1817	N08W	88W	reverse			Late Pleistocene	1		268	58
57	Morioto-Togashi	57-1	treaching	36.6239	136.7829	N08E	23E	reverse			Holocene	1		128	23
		57-2	natural outcrop	36.2981	136.2387	N6-10E	62E-vertical	reverse			Late Pleistocene	1		78.5	76
58	Fukuhara-jishan	58-1	natural outcrop	36.2989	136.2777	N6E	88E-vertical	left-lateral, reverse			Late Pleistocene	1		95	85
		58-2	treaching	36.2989	136.2777	N6E	88E-vertical	left-lateral, reverse			Late Pleistocene	1		95	85
59	Hagunaga-joryu	59-1	natural outcrop	35.8222	136.9229	N0E	48-50E	left-lateral			Late Pleistocene	1		265	72.5
		59-2	treaching	35.8222	136.9229	N0E	48-50E	left-lateral			historical (1881)	1		265	72.5
60	Nabi	60-1	treaching	35.8588	136.5888	N08W	88W	left-lateral			historical (1881)	1		239	88
		60-2	treaching	35.512	136.7883	N08W	vertical	left-lateral			historical (1881)	1		38	90
		60-3	treaching	35.5227	136.7883	N08W	vertical	left-lateral			historical (1881)	1		38	90
		60-4	natural outcrop	35.5857	136.6878	N08W	63E	left-lateral			historical (1881)	1		47	63
		60-5	treaching	35.5771	136.6878	N08W	63E	left-lateral			historical (1881)	1		47	63
		60-6	treaching	35.7958	136.4818	N08W	70-75W	left-lateral			historical (1881)	1		58	72.5
		60-7	treaching	35.6251	136.4818	N08W	vertical	left-lateral			historical (1881)	1		58	72.5
		60-8	treaching	35.7336	136.4275	N08W	vertical	left-lateral			in the past 2000 years	0.5	close to 60-9	58	72.5
		60-9	treaching	35.7384	136.4284	N08W	88W-vertical	left-lateral			in the past 2000 years	0.5	close to 60-8	28	75
		60-10	natural outcrop	35.6124	136.6818	N08W	85W	left-lateral			Late Pleistocene	1		85	85
61	Yamagata	61-1	natural outcrop	35.5438	136.289	N43W	58W	left-lateral			Late Pleistocene	1		227	88
		61-2	natural outcrop	35.8881	136.1211	N43W	vertical	left-lateral			Holocene	1		66	96
		61-4	natural outcrop	35.6884	136.1768	N27	28 E-48W	left-lateral			historical (1325)	1		235	71.5
		61-6	natural outcrop	35.7889	136.1386	N08W	23W-30E-48E	left-lateral			Holocene	1		75	55
		61-7	treaching	35.4567	136.3384	N08W	vertical	left-lateral			Holocene	0.5	close to 61-8	38	90
62	Sakigawa	62-1	natural outcrop	35.4579	136.1325	N08W	vertical	left-lateral			Holocene	0.5	close to 62-2	38	90
		62-2	treaching	35.3759	136.481	N43W	80E	reverse			Holocene	1		76	88
63	Hosono-Sadogaji	63-1	treaching	35.6888	136.8378	N08W	88W	left-lateral			historical (1887)	1		21	90
		63-2	treaching	35.6888	136.8378	N08W	88W	left-lateral			historical (1887)	1		21	90
64	Kohakusanji	64-1	pit excavation	35.5783	136.1852	N08W	88W	right-lateral			in the past 2000 years	1		128	78
		64-2	pit excavation	35.5444	136.8887	N02E	78E	right-lateral			Holocene	0.5	close to 64-3	135	78
		64-3	treaching, pit excavation	35.5444	136.8887	N02E	78E	right-lateral			in the past 2000 years	1		128	78
		64-4	treaching	35.5338	136.8336	N20E	45E	right-lateral, reverse			historical (1325)	1		118	45
65	Binkawagen	65-1-1	setatic profiling	35.1572	135.3244	N23W	48E (8-26m depth)	reverse			Late Pleistocene	0.5	close to 65-1-2	255	48
		65-1-2	setatic profiling	35.1572	135.3244	N23W	48E (8-26m depth)	reverse			Late Pleistocene	0.5	close to 65-1-1	255	48
		65-2	treaching	35.4739	136.8246	N20E	30W	reverse			Holocene	1		280	38
		65-3	treaching	35.4689	136.8246	N20E	21-30W	reverse			Holocene	1		280	22.5
		65-4-1	treaching	35.3638	136.8246	N02E	23W (No. 1 trench)	reverse			Holocene	0.333	close to 65-4-2, 1	280	25
		65-4-2	treaching	35.3638	136.8246	N02E	38W (No. 2 trench)	reverse			Holocene	0.333	close to 65-4-1, 1	278	58