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Stability of the regional stress field in central Japan during the late Quaternary

inferred from the stress inversion of the active fault data

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ABSTRACT

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

1. Introduction

The crustal stress field is one of the most important parameters required to understand tectonics, but the secular variation or stability of tectonic stress is not adequately understood for the time scales of $10^3$–$10^5$ years. The World Stress Map (WSM) Project was the first coordinated effort to map tectonic stress fields worldwide [Zoback, 1992], and the WSM database released in 2008 [Heidbach et al., 2010] contains three times as much stress data as that of the 1992 database. Most of the data sets used to derive the stress fields in the project are geophysical data such as those derived from the focal-mechanism solutions of earthquakes and wellbore breakout. In 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
stress-tensor inversion, as described below.

Stress-tensor inversion is used to determine stress conditions from the fault-slip data.

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

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

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

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

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

The fault-slip data set used in this study had a few deficiencies. Slickenlines were 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 $\sigma_1$-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 $\sigma_2$ is approximately equal to that of $\sigma_3$. 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 $\Phi$ value (axial compressional stress), the $\sigma_3$-axis has a greater uncertainty than that of the $\sigma_1$-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 $\sigma_1$-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 $\sigma_1$-axis. Theoretical slip directions on such fault planes are unstable as is shown by the radial pattern around the $\sigma_1$-axis in Figure 5. Therefore, small perturbations in fault attitudes can explain the large misfits.

The optimal stress ratio of 0.09 indicates that $\sigma_2$ and $\sigma_3$ 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 temporally 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 ~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 ~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...
in the eastern part of southwest Japan has been stable over the past ~10^5 years.
Moreover, the inversion results provide a clear explanation for the coexistence of
reverse and strike-slip faults in central Japan. Geological observations suggest that a
few active faults in central Japan reactivated pre-existing faults under the present-day
stress regime.

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**Figure captions**

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

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

Figure 5. Optimal stress axes (open stars) and calculated theoretical slip directions (white arrows) plotted on a tangent-lineation diagram with a lower-hemisphere, equal-area projection. The fault-slip data are the same as that in Figure 3. The fault-slip data shown in red are inconsistent with the theoretical slip directions. Note that most of the data agree with the theoretical slip directions.
N = 169

Fault-slip data

→ Complete data

Sense-only data
Fault-slip data with small misfit with large misfit

Complete data → →
Sense-only data ↓ ↓

Theoretical slip direction for optimal stress condition
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<th>Longitude</th>
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<th>Dip</th>
<th>Age</th>
<th>Distance</th>
<th>Friction</th>
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