Stress fields in and around metropolitan Osaka, Japan, deduced from microearthquake focal mechanisms

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1. Introduction

Knowledge of the tectonic stress field is of great importance for various fields of geoscience including the modeling of geodynamic processes and the evaluation of seismic hazards (e.g., Zoback, 1992). As for the seismic hazard assessment, slip tendency analysis (Morris et al., 1996) is an effective tool and has been successfully used to evaluate the seismic slip potential along known or suspected faults in a given stress field (e.g., Worum et al., 2004). However, the evaluation crucially depends on the adopted stress field, so we need to know a local-scale stress pattern near the faults that is as detailed as possible.

The Osaka urban region, which is the financial center of western Japan, has a population exceeding eight million. A number of active faults are concentrated within the area, including E-W - to NE-SW-trending strike-slip faults and N-S-trending reverse faults (e.g., Nakata and Imaizumi, 2002; Research Group for Active Faults of Japan, 1991). The Uemachi fault zone, an east-dipping blind reverse fault, traverses the center of the city of Osaka (Fig. 1). According to the Headquarters for Earthquake Research Promotion (2004), the Uemachi fault zone has the potential for generating an earthquake with a magnitude (M) of about 7.5, which is a significant seismic source for the city and the surrounding region. The Central Disaster Prevention Council of the Cabinet Office of the Japanese Government (2007) estimated that in the worst-case scenario, an earthquake in the Uemachi fault zone would cause about 42,000 deaths, a million collapsed buildings, and economic damage of 74 trillion Yen. Various geological, geomorphological, and geophysical surveys have been undertaken in the Osaka region to reveal the paleoseismicity, fault slip rate, and deep geometry of the fault zone, together with the subsurface structure (e.g., Horikawa et al., 2003; Ministry of Education, Culture, Sports, Science and Technology in Japan, 2013; Nakata et al., 1996; Okada and Chida, 1996; Sugiyama et al., 2003). Information obtained from these surveys is of great importance for the long-term evaluation of seismic activity, evaluation of strong ground motion, and development of possible earthquake scenarios (e.g., Kase et al., 2003). Regarding the crustal stress field of the Japanese islands, there exist stress maps based on earthquake data (e.g., Terakawa and Matsu‘ura, 2010; Townend and Zoback, 2006; Tsukahara and Kobayashi, 1991), showing that the present-day south-west Japan is generally under E-W compression. To data, however, the stress field has not been described within the Osaka region (i.e. on a local scale), which is information necessary for the evaluation of the slip potential along the Uemachi fault zone as well as for the improvement of the accuracy of the above studies.

Among the various stress indicators such as in-situ stress measurements and strain data, earthquake focal mechanisms are considered...
the most effective means by which to constrain the stress field at the depth of earthquake occurrence. The main obstacle to seismic observation in urban areas is background noise produced by human activities such as road traffic and industrial work. The National Research Institute for Earth Science and Disaster Prevention (NIED) constructed four deep borehole observatories in the Kanto area including Tokyo, the capital city of Japan, showing a remarkable improvement of microearthquake detection capability (Suzuki, 1996; Takahashi, 1982). These borehole observatories together with the surrounding high-sensitivity seismograph network contributed to the understanding of seismotectonics and seismogenic processes beneath Tokyo (e.g., Ishida, 1992). Following the disastrous 1995 Mw 6.9 Hyogoken-nanbu (Kobe) earthquake, a densely distributed high-sensitivity borehole seismograph network covering all Japan (Hi-net) has been constructed, which is operated by NIED (Okada et al., 2004). Most of the Hi-net seismometers were installed at depths of a few hundred meters, but some specific sites have boreholes deeper than 1000 m (three sites in Tokyo prefecture). In addition, the Geological Survey of Japan, AIST (GSJ) has created an integrated borehole network for observing subsurface water levels, water temperatures, crustal strain, tilt, and seismic waves. This network is concentrated mainly in southwest Japan, where high-sensitivity seismometers have been installed at depths of about 30–800 m (Imanishi et al., 2011b; see also https://gbank.gs.j.jp/wellweb/GSJ_E/tmp/gaiyoue.html#40 (Accessed: June 30, 2014)). In particular, there is an observatory at a depth of 543 m in the central part of the Uemachi fault zone. These borehole seismic observations can significantly enhance the capability for microearthquake detection, providing a unique opportunity for the retrieval of focal mechanisms and tectonic stresses in noisy urban Osaka area.

In this study, we infer the present-day stress fields in and around metropolitan Osaka from the population of focal mechanism solutions over approximately the past 10 years. Because most earthquakes that occur within the area are smaller than M2.0, we attempt to determine the focal mechanisms using P-wave polarity data in conjunction with body wave amplitudes, which permits us to obtain numerous well-determined solutions. Based on the estimated stress fields, we can for the first time evaluate the slip potential of the Uemachi fault zone using slip tendency analysis (Lisle and Srivastava, 2004; Morris et al., 1996).

2. Seismological and tectonic setting

In southwestern Japan, the Philippine Sea Plate is being subducted northwestward beneath the Japanese Islands at a convergence rate of ~40 mm/yr (e.g., Seno et al., 1993) (Fig. 1). M8-class megathrust earthquakes have occurred repeatedly along the plate boundary with an interval of 100–150 yrs (e.g., Ando, 1975). The latest events were the 1944 M7.9 Tonankai and 1946 M8.0 Nankai earthquakes, which ruptured different segments of the plate boundary (Baba and Cummins, 2005). The crustal stress field in southwest Japan is basically characterized by a subhorizontal E-W compression as indicated by P-axis distribution of earthquake focal mechanisms (Tsukahara and Kobayashi, 1991), stress tensor inversion using earthquake focal mechanisms (Townend and Zoback, 2006) or centroid moment tensors (Terakawa and Matsu’ura, 2010), in-situ stress measurements (e.g., Tanaka, 1985), and geological evidence (e.g., Sugiyama, 1994). The strike-slip faulting stress regime predominates the southwest Japan, but the reverse-faulting one regionally prevails in the eastern part (e.g., Terakawa and Matsu’ura, 2010; Townend and Zoback, 2006; Tsukahara and Kobayashi, 1991). The region roughly corresponds to the Kinki Triangle Zone (Huzita, 1962), which is characterized by a dense distribution of primarily N–S-trending active reverse faults (Nakata and Imaizumi, 2002; Research Group for Active Faults of Japan, 1991).

The present study area (a blue box in the right of Fig. 1) is situated within the western part of the Kinki Triangle Zone, bounding to the north by Arima–Takatsuki Tectonic Line, which is a dextral strike-slip fault and to the south by the E–W-striking Median Tectonic Line. The 1995 Mw 6.9 Kobe earthquake occurred on NE-striking Median Tectonic Line. The 1991 Mw 6.9 Kobe earthquake is marked with a Centroid Moment Tensor solution by JMA (http://www.data.jma.go.jp/svd/eqev/data/mekh/pdf/cmt1995.pdf (Accessed: June 30, 2014)).

Fig. 1. (a) Tectonic setting of Japanese islands. Kinki Triangle Zone (KTZ) (Huzita, 1962) is shown by a green triangle. (b) Enlarged map of red rectangle shown in a depicting active faults and shallow background seismicity in and around the study area. Red lines show active faults after Nakata and Imaizumi (2002); Uemachi fault zone (UMF) and Ikoma fault zone (IKF) are indicated by bold lines. Circles represent M1+ earthquake locations shallower than 20 km determined by the Japan Meteorological Agency (JMA) during the period January 2001 to December 2011. Blue rectangle defines the present study area. The 1995 Mw 6.9 Kobe earthquake is marked with a Centroid Moment Tensor solution by JMA [http://www.data.jma.go.jp/svd/eqev/data/mech/pdf/cmt1995.pdf (Accessed: June 30, 2014)).
Uemachi fault zone as an approximately 42-km long east-dipping reverse fault with a strike ranging from N10°W to N20°E (UMF in Fig. 1). The Ministry of Education, Culture, Sports, Science and Technology in Japan (MEXT, 2013) conducted comprehensive research on the Uemachi fault zone, which provided important information regarding the development of plausible earthquake scenarios. That report suggested that the late Quaternary cumulative deformation could not be identified in the northern 5 km of the Uemachi fault zone. Instead, the 26-km-long coastal fault from approximately 34.35°N 135.23°E to 34.51°N 135.42°E, with a strike of about N45°E, was newly recognized as part of the Uemachi fault zone. Deformation recorded in growth strata indicates that the average vertical slip rate is at most 0.6 mm/yr, the recurrence interval is longer than about 7000 yr, and that the most recent earthquake on the fault zone occurred after approximately 2700 yr BP. Regarding the Ikoma fault zone, which is an approximately 38-km-long east-dipping reverse fault (IKF in Fig. 1), the Headquarters for Earthquake Research Promotion (2001) showed that the average vertical slip rate is 0.5–1.0 mm/yr, the recurrence interval is 3000–6000 yr, and that the most recent earthquake occurred approximately 400–1000 yr BP. Based on careful consideration of ancient writings, Hagiwara (1989) suggested that an earthquake in 734 (M7.0) could be a candidate for the most recent destructive earthquake on the fault zone.

Fig. 1 also illustrates the shallow seismicity in and around the study area during the period from January 2001 to December 2011, as routinely determined by the Japan Meteorological Agency (JMA). It can be seen that there are some regions with high levels of seismicity: the Tanba district lying to the north of the study area, swarm-like activity in the Wakayama district lying to the southwest of the study area, and aftershocks of the 1995 Kobe earthquake. Background seismicity within the study area is quite low compared with these regions, but M4.0 or larger earthquakes do occasionally occur.

The black “beach balls” in Fig. 2 show the focal mechanisms of earthquakes that occurred during the period from October 1997 to December 2011 at depths shallower than 20 km, which have been determined by the JMA based on observations of P-wave first motion polarities. The JMA generally reports focal mechanisms for earthquakes greater than M3.0, which is insufficient for discussions on the local tectonic stress prevailing within the study area. Using the newly deployed seismic observatories of the Committee of Earthquake Observation and Research in the Kansai Area, which are distributed within the study area, Nakamukae et al. (2003) determined the focal mechanisms of earthquakes down to M1.5 that occurred during the period from 1995 to 1999 (gray beach balls in Fig. 2). The two data sets show that in addition to earthquakes with a pure reverse-fault mechanism, earthquakes with strike-slip components do occur, which is inconsistent with the faulting style of the Uemachi and Ikoma fault zones. Although the P-axes are on average oriented to the general E–W trend of the region (e.g., Terakawa and Matsu’ura, 2010; Townend and Zoback, 2006; Tsukahara and Kobayashi, 1991), they do appear to differ slightly depending on their location. These observations imply spatial variation within the local stress field, but the small number of available focal mechanisms precludes detailed investigation.

3. Data

We selected a rectangular area (blue box in Fig. 1 and dashed box in Fig. 2) for the present study area, which includes both the Uemachi and Ikoma fault zones, part of the Rokko fault zone, and the Median Tectonic Line active fault zone. Fig. 3 shows the distribution of the permanent stations used in this study, operated by the NIED, JMA, GSJ, Earthquake Research Institute (University of Tokyo), and Disaster Prevention Research Institute (Kyoto University). Each station is equipped with a set of three-component velocity transducers having a natural frequency of 1 or 2 Hz. As already mentioned, seismometers operated by the NIED and GSJ are installed at the bottom of boreholes.

We analyzed 261 earthquakes that occurred between June 2002 and October 2011, which had JMA magnitude (Mj) >1 and focal depth <20 km. The locations of these earthquakes are shown by shaded circles in Fig. 3. Of these earthquakes, 227 events (87%) were less than Mj2.0; the largest event was Mj4.1. Fig. 4 shows an example of the vertical component seismograms of an Mj1.1 earthquake that occurred near the middle of the Uemachi fault zone. Four seismograms recorded in boreholes are enlarged, showing that the P-wave onset polarity of the microearthquake can be clearly identified. These borehole data provide a unique opportunity for retrieving the focal mechanisms and tectonic stress, even in noisy urban environments.

4. Hypocenter determination

We determined the hypocenters of the earthquakes by applying a maximum-likelihood estimation algorithm (Hirata and Matsu’ura, 2010).
to picked arrival times. The P- and S-wave arrival times were identified manually using the WIN system developed by Urabe and Tsukada (1991). The P-wave velocity model used in our investigation is a one-dimensional velocity structure based on the tomography results of Matsubara et al. (2008), which consists of four layers. The S-wave models are assumed by scaling the P-wave velocities by a factor of $1/\sqrt{3}$. We first located the hypocenters of all the events without station corrections. We then relocated them by introducing the station corrections, which were obtained using the average of the differences between the observed and theoretical travel times at each station. We repeated the above procedure until the reduction of the root mean square of the arrival time residuals (RMS) became less than 0.01 s and obtained the final locations as well as station corrections for each station. We then determined the spectral levels and deployed an attenuation correction. The spectral levels were used as the depth range of 0–9 km. The blue circles in Fig. 6 show earthquakes of M3.0 or greater, indicating that larger events tend to occur at the base of the seismogenic zone. A similar pattern has also been reported in other continental areas around the world (e.g., Boese et al., 2012; Spada et al., 2013; Yang and Hauksson, 2011). Fig. 7 presents the earthquake hypocenters projected onto profiles almost perpendicular to the Uemachi and Ikoma fault zones. We also show the deep fault geometries of the Uemachi fault zone, which are inferred from a 3-dimensional balanced cross-sectional analysis assuming that the strata of the marine clay on the hanging wall side has been deformed as fault-related folds (MEXT, 2013). Considering the deep fault geometry of the Uemachi fault zone, it can be seen that the seismicity distributed near the surface traces of the fault occurs primarily on the footwall side. The profile A–A’ shows three alignments that appear related to fault structures. The alignment a is located on the east side of the Uemachi fault zone and has an eastward-dipping plane with an angle of about 30°. However, the alignment location does not always coincide with the inferred deep fault geometry of the Uemachi fault zone, but appears located at the point where the fault dip changes from steep to gentle. The alignments b and c are located on the east side of the Ikoma fault zone and have an eastward-dipping planes with angles of about 50° and 20°, respectively. Both alignments could be part of the deeper portion of the Ikoma fault zone. The seismicity in the profiles B–B’ and C–C’ shows some small-sized clusters, but it is difficult to identify clear alignments associated with the fault zones.

5. Stress field in and around the Uemachi Fault Zone

5.1. Focal mechanism solution of microearthquakes using body wave amplitudes

In this study, we determined focal mechanism solutions using P-wave polarity together with absolute P and SH amplitudes. The same approach has been used in previous studies (e.g., Imanishi et al., 2011a) and shown to be effective for microearthquakes. We analyzed earthquakes with at least 10 P-wave polarities. After applying corrections for instrument response, we determined the spectral levels and corner frequencies of the spectra by fitting the $\omega^2$ model (Boatwright, 1978) with an attenuation correction. The spectral levels were used as observed amplitudes in the preceding analysis. Theoretical amplitudes
were computed based on the far-field solutions of a shear point-source dislocation in a homogeneous infinite medium, with corrections for the incident angles at the surface and geometrical spreading. The best-fit solution for each event was determined by minimizing the residual between the observed and theoretical amplitudes, for which a grid search was performed using a 5° grid for strike, dip, and slip angles. We first determined the focal mechanisms and seismic moments for all events and then re-determined them by introducing the amplitude station correction, obtained using the logarithmic average of the ratios between the theoretical and observed amplitudes at each station. The stability of the solution was verified by plotting all focal mechanisms whose residual was within 1.1 times that of the minimum value. We rejected ambiguous solutions where multiple solutions were possible. In total, we obtained 238 focal mechanisms whose moment magnitudes ranged from 1.4 to 3.7. We defined focal mechanism uncertainties for each event based on the average of the Kagan angles (Kagan, 1991) between the best-fitting solution and all the solutions whose residual was less than 1.1 times the minimum residual value. Here, the Kagan angle becomes 0° when the two mechanisms are the same and 120° when they differ most. The average uncertainty of all the focal mechanisms was 20°. The focal mechanisms and their faulting type are plotted in Fig. 8a. A triangle diagram (Flohlich, 1992) with a color scale is presented to the right of Fig. 8a, in which the different colors illustrate the faulting type: reverse (green), strike-slip (red), and normal (blue). Following the definition of Frohlich (1992), we categorized reverse events as those having T-axis plunges of less than 40°, and strike-slip and normal fault earthquakes as those having B- and P-axis plunges of less than 30°, respectively. All remaining events were defined as

Fig. 6. Hypocenter distributions determined in the present study. The bottom six panels show earthquakes in each consecutive 3-km depth interval from 0 to 18 km. Circles in blue represent earthquakes of M3 or greater. Boxes in the top panel labeled A–A′ through C–C′ are used for plots in Figs. 7 and 9. Inverted triangles show reference locations of the Ikoma fault zone for each box.
The directions of the P- and T-axes are shown in Fig. 10, where different colors are used to represent different plunge angles. Most of the P-axes are sub-horizontal and oriented in ESE–WNW to ENE–WSW directions, which conforms to the general tectonic trend within this area (e.g., Terakawa and Matsu’ura, 2010; Townend and Zoback, 2006; Tsukahara and Kobayashi, 1991). The T-axes have a wide range of plunge, indicating the coexistence of reverse and strike-slip faulting earthquakes.

The focal mechanisms alone do not adequately represent the stress field, because the direction of the P- and T-axes can differ from the maximum and minimum principal stresses by 45°, respectively (McKenzie, 1969). In the following, we invert for the orientations of the principal stresses and their relative magnitude from the population of focal mechanisms.

5.2. Stress tensor inversion

Using the focal mechanism solutions determined in the previous section, we estimated the stress field within the study area by applying the inversion method of Michael (1984). The inversion solves the orientation of the three principal stress axes together with the relative magnitude of the principal stresses defined by $\phi = (S_2 - S_3) / (S_1 - S_3)$, where $S_1$, $S_2$, and $S_3$ are the maximum, intermediate, and minimum compressive principal stresses, respectively. One plane must be chosen from each focal mechanism as the actual fault plane, because the inversion uses the direction of the tangential traction on the fault plane. We chose the preferred planes while inverting for the stress tensor based on Michael’s (1987) grid search algorithm, which is considered to be a rational approach in situations where the choice of fault plane cannot be made based on relative hypocentral locations or geological information (e.g., Kastrup et al., 2004). There are four parameters in the grid search algorithm: the trend and plunge of the S1 axis, a rotation angle of the S2 axis about the S1 axis, and $\phi$. The grid search was performed using a 5° grid for all of the angular variables and a step of 0.1 for $\phi$. To calculate confidence regions for the stress tensor, we applied the bootstrap resampling technique by assuming that a certain percentage of the planes would be picked incorrectly (Michael, 1987). In the present study, for the bootstrap, we assumed that each nodal plane had the same probability of being selected during the resampling. Following Michael (1987), we used 2000 bootstrap samples to obtain the 95% confidence region.

We divided the focal mechanism data set into nine areas (A1 to A9) based on earthquake locations (Fig. 11). The number within each set of parentheses indicates the number of events used for the inversion. We excluded 3 normal fault events together with 11 events whose P-axis directions obviously deviated from the general tectonic trend, because they made the inversion unstable. We believe that these events were associated with a local heterogeneous stress field. The results of the stress tensor inversion are shown in Fig. 12. The average misfit angles $(\beta)$ between the predicted tangential traction on the fault planes and the observed slip direction on each plane range from 13° (area A2) to 34° (area A8), suggesting a valid fit to the single stress tensor (Michael, 1991). For each area, the maximum principal stress $S_1$ is clearly differentiated from $S_2$ and $S_3$, trending sub-horizontally from ESE–WNW to ENE–WSW. The $S_2$–$S_3$ plane rotates around the $S_1$ direction, which gives rise to a spatial dependence in the stress field. Based on the definition of Zoback (1992), and using the best stress axes for each area, the stress regime is categorized as reverse faulting (RF) for area A6, predominantly reverse faulting with a strike-slip component (RS) for areas A5 and A9, and strike-slip faulting (SS) for the remaining areas. The stress ratio $\phi$ is basically less than 0.5 and therefore, the magnitude of $S_2$ is closer to $S_3$ than $S_1$. In other words, the magnitude of $S_1$ is prominent throughout the studied area, showing smaller variation in the $S_1$ orientation compared with the other two principal stresses.

Following the method of Lund and Townend (2007), we computed the true axis of maximum horizontal compressive stress $(S_{hmax})$ from...
the four stress parameters determined by the stress tensor inversion (the directions of the three principal stresses and the stress ratio $\phi$).

Fig. 13 displays rose diagrams of $S_{\text{Hmax}}$ orientations computed from the stress parameters that are within the 95% confidence regions. Here, the bars are colored according to the stress regime, which we described in the above paragraph. Also shown are the $S_{\text{Hmax}}$ orientations and faulting regimes reported by Townend and Zoback (2006), which were extracted from the World Stress Map database (Heidbach et al., 2008). The $S_{\text{Hmax}}$ orientation observed throughout the region is almost uniform from E–W to ESE–WNW, although small local fluctuations in the counterclockwise direction can be identified (e.g., A6 and A9).

With regard to the stress regime, strike-slip faulting prevails throughout the region; however, we also found a reverse-faulting regime, especially in the southern part of the region that includes area A6. In other words, it is indicated that there is a locally increased reverse component in the middle and southern parts of the Uemachi fault zone.

6. Slip tendency analysis

We assessed slip potential of the Uemachi fault zone under the estimated stress fields using a slip tendency analysis (Morris et al., 1996). In the present study, we do not examine the slip tendency of the Ikoma...
fault zone and a newly recognized part of the Uemachi fault zone as mentioned in the Section 2, because the deep geometry of these faults is not yet clearly understood. Slip tendency ($T_s$) is based on the notion that slip on a fault is controlled by the ratio of shear stress ($\tau$) to effective normal stress ($\sigma_n$) acting on the plane of weakness; hence, it is defined as $T_s = \tau / \sigma_n$. Lisle and Srivastava (2004) introduced normalized slip tendency as $T_s' = T_s / \mu$, where $\mu$ is the coefficient of static friction. $T_s'$ ranges from 0 to 1, where the larger value indicates greater slip probability. We supposed that the frictional sliding envelope is tangential to the $S_1$–$S_3$ Mohr circle, which makes it possible to compute $T_s'$ without knowledge of the absolute stress value (Lisle and Srivastava, 2004). Following Collettini and Trippetta (2007), we defined favorably oriented planes for $0.5 \leq T_s' \leq 1.0$ and poorly oriented planes for $0 \leq T_s' \leq 0.5$.

Based on mapped fault traces, we considered three different fault orientations: 350°, 5°, and 20° for the northern, middle, and southern sections of the fault zone, respectively (Fig. 14a). We assumed that the fault plane dips at 60° in the shallower part and at 30° in the deeper part for the northern and middle sections, and at 45° for the southern section, as suggested by a balanced cross-sectional analysis (MEXT, 2013) (Fig. 7). We applied the stress fields estimated in areas A4, A5, and A6 (Fig. 12) to the northern, middle, and southern sections of the fault zone, respectively. The coefficient of static friction $\mu$ was set to 0.6, which in general is considered suitable for seismogenic faults.
The Wallace–Bott hypothesis (Bott, 1959; Wallace, 1951) states that slip on faults occurs in the direction of maximum resolved shear stress. Based on their hypothesis, the currently assumed stress fields favor reverse faulting in the middle section, but oblique slip faulting in the northern and southern sections. High-resolution seismic reflection profiles and boring core data indicate that the vertical cumulative displacements by the Uemachi fault reach a few hundred meters, while the lateral displacements are not remarkable (e.g., Headquarters for Earthquake Research Promotion, 2004; Sugiyama et al., 2003). Following this observation, we computed the normalized slip tendency using the component of shear stress acting in the slip direction of 90° on a fault (a pure dip-slip faulting) instead of the shear stress itself. We termed this the normalized dip-slip tendency ($T_{ds}'$) to avoid confusion with the original definition of $T_{rs}'$ (Fig. 14b). Open bars and open inverted triangles in Fig. 14d show the frequency of $T_{ds}'$ computed from the 95% confidence regions of the assumed stress fields and the $T_{ds}'$ of the best stress solution, respectively. Because the directions of maximum shear stress resolved on the fault planes of the middle section are approximately 90°, the computed values of $T_{ds}'$ are almost consistent with those of $T_{rs}'$. Therefore, the shallower part of the middle section (dip 60°) is considered unfavorably oriented for failure in the present-day stress fields. This is a natural consequence because it is difficult for high-angle reverse faults to reactivate under horizontal compression. However, for the northern and southern sections, where oblique faulting is expected, the values of $T_{ds}'$ generally become smaller compared with those of $T_{rs}'$. The computed values of $T_{ds}'$ of the best stress solution, together with the majority of the 95% confidence regions, fall below 0.5 for the northern section (both the shallower and the deeper parts), but still exceed 0.5 for the southern section. The reason why the northern section results in an unfavorable orientation in terms of pure reverse faulting is largely associated with the lack of a reverse-faulting component in its applied stress field. It is noted that this result supports the geological observation that the late Quaternary cumulative

![Fig. 12. Stress tensor inversion results for each area. Left-hand panels show principal stress axes with their 95% confidence regions plotted on lower hemisphere stereonets. Upper-right panels show the misfit angle for the data with respect to the best stress tensor determined by the stress tensor inversion, where the misfit angle represents the angle between the tangential traction predicted by the best solution and the observed slip direction on each plane determined from the focal mechanism. Lower-right panels show the frequency of the stress ratio $\phi$, which belongs to the 95% confidence region.](image-url)
deformation cannot be identified in the northern 5 km of the Uemachi fault zone (MEXT, 2013). Thus, we conclude that the middle (only the deeper part) and southern sections have greater potential for reactivation of reverse faulting.

7. Discussion

We determined earthquake distribution and local stress fields in and around metropolitan Osaka using microearthquake data down to M1.0, which has filled the gap in the stress fields left by previous studies (e.g., Townend and Zoback, 2006) (see Figs. 2 and 13). The inferred stress fields are generally coincident with those observed in surrounding areas, especially with regard to the orientation of $S_{\text{thmax}}$. However, with a scale of at least 10 km, there are small but noticeable differences in both $S_{\text{thmax}}$ and the stress regime. These local fluctuations actually affect the evaluation of slip potential on the fault, emphasizing the importance of creating local-scale stress maps that are as detailed as possible.

The depth distribution of focal mechanisms implies that reverse-faulting earthquakes occur throughout the seismogenic zone, while a relatively larger number of strike-slip earthquakes occur at the base of the seismogenic zone (Fig. 9). Ito (1996) found a similar depth variation in focal mechanisms of earthquakes in the Tanba district, which lies to the north of the study area, where both strike-slip and reverse-fault events are found throughout the seismogenic zone, and strike-slip earthquakes become predominant in the deeper part of the seismogenic zone. Ito (1996) inferred that the minimum horizontal compressional stress (the N–S orientation) becomes lower than the vertical stress below the brittle layer due to brittle–semi-brittle transitional behavior, which could possibly explain the observational evidence that earthquakes occurring at deeper parts of the seismogenic zone are dominated by a strike-slip component. Here, based on the results of deep crustal seismic surveys (Ito et al., 2006), we will present another mechanism that could account for a change in stress field with depth. Ito et al. (2006) conducted seismic refraction and wide-angle-reflection surveys of the crust and upper mantle structure, the survey line of which is located along the eastern part of the present study area (approximately from 33.72°N 135.95°E to 35.42°N 135.42°E), cutting almost perpendicular to the Median Tectonic Line and the Arima-Takatsuki Tectonic Line. They found clear reflectors in the lower crust at depths from about 15 and 35 km, which gently decline towards the north. If these reflectors represent fault planes and aseismic slip occurs along them, then the N–S tensional stress above the reflector planes would be caused by the hanging wall side being pulled southward in the case of reverse-faulting slip and northward in the case of normal-faulting slip. We infer that the induced tensional stress reduces the N–S compressional stress and strike-slip-faulting earthquakes become dominant at the base of the seismogenic zone. However, the present study alone cannot constrain the type of faulting that is favored along the reflector planes, because the stress field there is unknown.

We have discussed the deviatoric part of the stress tensor, because stress fields estimated from focal mechanisms do not yield absolute values of the principal stresses. However, information regarding absolute stress over a seismogenic zone is essential for understanding the process of earthquake generation. The $b$-value of the Gutenberg–Richter law (Gutenberg and Richter, 1944) has been shown to be inversely proportional to differential stresses (e.g., Amitrano, 2003; Schorlemmer et al., 2005; Spada et al., 2013), suggesting that the $b$-value can be used as a proxy for a stress meter of the Earth’s crust. In the present study, we observed that larger events tend to occur at the base of the seismogenic zone (Figs. 6 and 7). Unfortunately, the small number of earthquakes precludes the computation of a reliable $b$-value, but it is likely that the $b$-value for the deeper part of the seismogenic zone would be lower than for the shallower part, implying that the deeper part is highly stressed. We believe that further longer-term seismic observation will reveal the spatial and depth distributions of $b$-values within the study area, which together with the estimated stress fields would contribute to the development of more accurate seismic-hazard assessment for metropolitan Osaka.

8. Conclusion

We have investigated stress fields in and around metropolitan Osaka, Japan, based on numerous focal mechanism solutions of microearthquakes over approximately the past 10 years. Borehole seismic observations allowed us to obtain 238 well-constrained focal mechanisms, even in a noisy urban environment, which has filled a gap in the stress fields left by previous studies. We found many earthquakes with a pure reverse-faulting mechanism throughout the studied area, which is consistent with the faulting style of active faults within the area (Uemachi and Ikoma fault zones). It was also found that a considerable number of microearthquakes occur with strike-slip components. This observation indicates that the area is characterized by a mixture of reverse- and strike-slip-faulting stress regimes. Most of the $P$-axes are sub-horizontal and oriented in the ESE–WNW to ENE–WSW directions, which conform to the general tectonic trend within this area. A stress tensor inversion revealed small but noticeable differences in stress regime, on a scale of at least 10 km, in which strike-slip faulting prevails over the region, but where the middle and southern sections of the Uemachi fault zone contain some reverse-faulting components. We assessed the reactivation potential of the Uemachi fault zone using slip tendency analysis under the estimated stress fields and assumptions regarding the deep fault geometry. The results indicate greater potential for reactivation in the middle and southern sections of the fault zone, which is associated with the locally increased reverse-faulting component.
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References


Fig. 14. Slip tendency analysis of the Uemachi fault zone. (a) Location of northern, middle, and southern sections of the fault zone. (b) Definition of normalized slip tendency \( T_s' \) and normalized dip-slip tendency \( T_{ds}' \). (c) The frequency of the normalized slip tendency \( T_s' \) computed from the 95% confidence region of the assumed stress fields. The inverted triangles represent the normalized slip tendency of the best stress solution (see the detail in the text). (d) The same as in c but for the normalized dip-slip tendency \( T_{ds}' \).