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

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ABSTRACT

Present-day stress fields in and around metropolitan Osaka, Japan, have been investigated based on 238 microearthquake focal mechanism solutions from approximately the past 10 years. The successful retrieval of the focal mechanisms in the noisy urban area owed much to the clean seismic data recorded at four borehole observatories deeper than 500 m depth in Osaka prefecture, in which P-wave onset polarity of the microearthquake could be clearly identified. We found many microearthquakes with a pure reverse-faulting mechanism, which is consistent with the faulting style of major active faults within the area (42-km long east-dipping Uemachi and 38-km long east-dipping Ikoma fault zones); however, a considerable number of microearthquakes with strike-slip components were also found to occur. Most of the P-axes are oriented in the ESE–WNW to ENE–WSW directions sub-horizontally, conforming to the general tectonic trend of the area. The analysis of a stress tensor inversion delineated small but noticeable differences in stress regime, on a scale of at least 10 km, where strike-slip faulting prevails throughout the region but the middle and southern sections of the Uemachi fault zone contain some reverse-faulting components. Based on the estimated stress fields, together with assumptions regarding the deep geometry of the Uemachi fault zone, we assessed the reactivation potential of the fault zone through slip-tendency analysis. The results indicate higher potential in the middle and southern sections of the fault zone, which is related to the locally increased reverse component detected there.

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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 southwest 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

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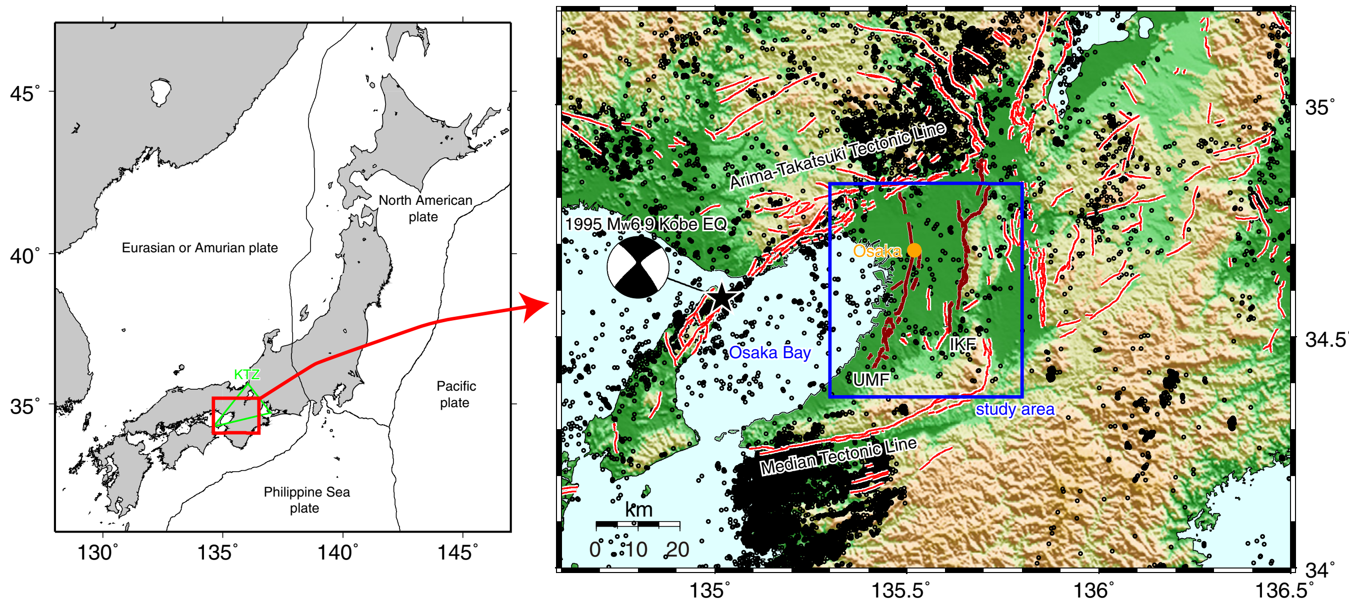

Fig. 1. (a) Tectonic setting of Japanese islands. Kinki Triangle Zone (KTZ) (Huzita, 1962) is shown by a green triangle. (b) Enlarged map of red rectangle shown in a depicting active faults and shallow background seismicity in and around the study area. Red lines show active faults after Nakata and Imaizumi (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 M_w6.9 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)).

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 M_w 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 Osaka 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.gsj.jp/wellweb/GSJ_E/tmp/gaiyoue.html#0 (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 M_w6.9 Kobe earthquake occurred on NE-striking strike-slip faults to the west of the region, causing over 6000 fatalities. The study area includes two major active faults: the Uemachi fault zone, traversing the center of the city of Osaka, and the Ikoma fault zone, which runs almost parallel to the Uemachi fault zone about 12 km further east. The Headquarters for Earthquake Research Promotion (2004) defined the

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