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Magnetotelluric survey of an active fault system in the northern part of Kinki District, southwest Japan

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Abstract—Combined geological and geophysical surveys are effective in finding hidden active faults and estimating the dimensions of their fracture zones in the northern part of the Kinki District, southwest Japan. The magnetotelluric method using electromagnetic energy in the ELF frequency band can define the dimensions of a fault and suggest whether it is active or not.

The results of the survey show that individual active strike-slip faults may be linked through new faults found in unexposed areas. The distribution of major active faults suggest that they form conjugate sets defining boundaries to tectonic blocks. At least seven tectonic blocks are recognized with different patterns of occurrence of microearthquakes and distributions of active faults. Historically large earthquakes, magnitude >5 as determined by maximum velocity amplitude, occur at the boundaries of the blocks. These patterns are caused by the different stress fields applied to each block.

INTRODUCTION

SINCE the relationship between faults and earthquakes was confirmed, it has been recognized that data on the distribution, length and movement rate of active faults are important to long-range earthquake prediction. Matsuda (1975) pointed out that the dimensions of an active fault have a close relationship to the maximum magnitude of earthquakes occurring on it. The dimensions of active faults have been determined by mapping their surface traces, but these are sometimes obscured by alluvium, when, for example, the erosion rate is faster than the movement rate. We believe geophysical prospecting methods are valuable in tracing hidden parts of a fault and thus defining its trace more completely.

In this study, geophysical prospecting, in addition to geological mapping, were used to determine the distribution of major active faults in the northern part of Kinki District, southwest Japan. The magnetotelluric (MT) electromagnetic method was mainly used in this survey. In this paper, we discuss the advantages of the MT method in mapping active faults and describe the features of active faults and the seismic activity around the tectonic blocks bounded by them.

ACTIVE FAULT SYSTEM AND EARTHQUAKE OCCURRENCE

Figure 1 shows the distribution of active faults in the northern part of Kinki District, known prior to this study, after the Electromagnetic Research Group for the Active Faults (1982). The epicenters of earthquakes of magnitude >2, as determined by maximum velocity amplitude, are based on data from the Tottori Microearthquake Observatory attached to Disaster Prevention Research Institute, Kyoto University. Most of the active faults in this area have a strike-slip movement. There are two patterns of fault strikes making a conjugate set; one is WNW–ESE to NNW–SSE and left-lateral, the other is NNE–SSW to ENE–WSW and right-lateral. Examples of the former are the Yamasaki, Yagi-Yabu and Mitoke faults, and those of the latter are the Yamada Fault and Arima-Takatsuki Tectonic Line (ATL). Reverse faults, e.g. Hanaori Fault and Rokkou fault system, appear in the eastern and southern parts of the district. These patterns reflect E–W to ESE–WNW compression caused by the subducting slab of the Pacific plate (Hujita *et al.* 1973). The movement rates of these faults in recent years are <1 mm yr^{-1} (Research Group for the Active Faults 1980).

The seismic belts where earthquakes occur frequently seem to be extended along these faults (Oike 1976), but do not always correspond to the active faults in some areas. These areas generally appeared as gaps between two large faults. We considered that an active fault has not been discovered yet in these gaps. In such cases, individual faults may be linked, thus, changing the evaluation of fault length and the interpretation of the tectonic features, including earthquake prediction.

SURVEY METHOD

The MT method is one of the electromagnetic prospecting methods developed in the 1960s (Vozoff 1972).

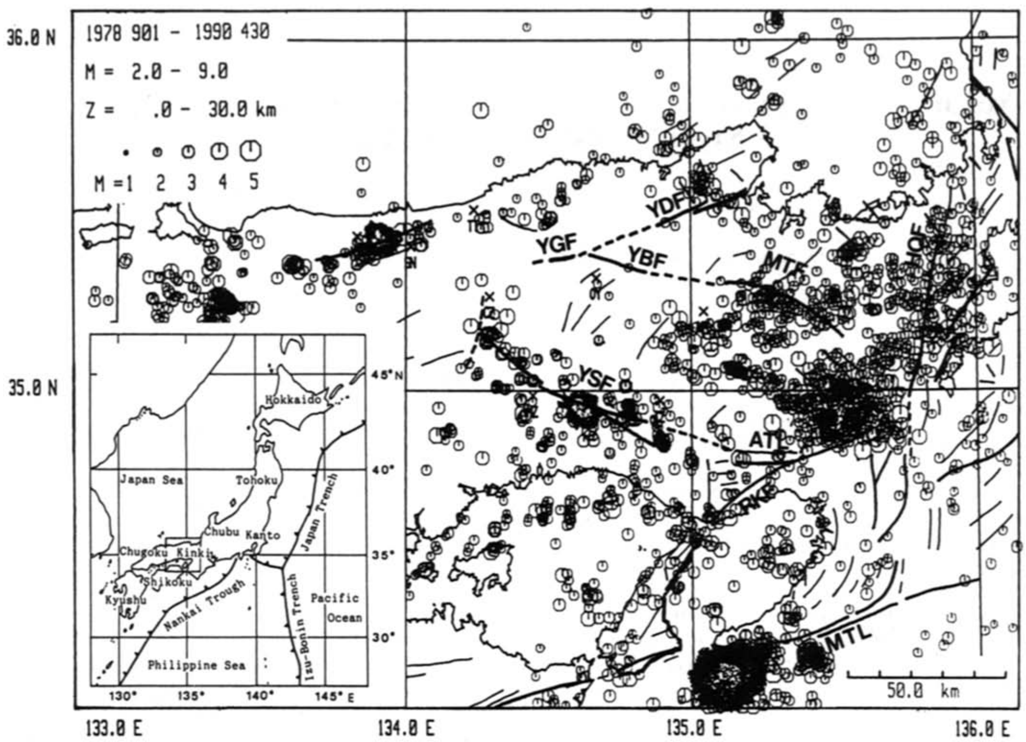

Fig. 1. Distribution of active faults (Research Group for the Active Faults 1980) and earthquake occurrence (M>2, Disaster and Prevention Research Institute, Kyoto University). Solid lines show the active faults known prior to this study, those with length >30 km are indicated by heavy lines. Broken lines show the active faults defined in this study. YSF, Yamasaki Fault; YGF, Yagi Fault; YBF,. Yabu Fault; MTF, Mitoke Fault; YDF, Yamada Fault; HOF, Hanaori Fault; ATL, Arima–Takatsuki Tectonic Line; RKF, Rokkou fault system; MTL, Median Tectonic Line.

Two orthogonal electric and magnetic components are measured at each station to obtain apparent resistivity values at a number of decreasing frequencies, providing resistivity information at progressively increasing depth, i.e. a form of vertical electrical sounding. This method has been successfully applied to detect electric conductors in the shallow part of the crust, e.g. in geothermal explorations (Hoover *et al.* 1978) and mineral exploration (Strangway *et al.* 1973). The ELF–MT system used in this study was described in detail by Handa & Sumitomo (1985) and Mogi *et al.* (1986). The method uses natural electromagnetic signals at frequencies of 8–40 Hz (Schumann Resonance frequency range) and the artificial signal at 17.4 kHz from the military transmitting station in Yosami, central Japan. The intensity of signals in this frequency range is fairly high (Ogawa *et al.* 1967). The measuring system is light and portable, and provides scalar values of apparent resistivity, which may be inverted to obtain a simplified sub-surface layer structure. The maximum depth of investigation is estimated at 1.3 km in 100 ohm-m earth and 4.0 km in 1000 ohm-m earth using the Bostick Depth (Bostick 1977).

When applied to the survey of active faults, the MT method has several advantages. Firstly, provided the measuring direction of magnetic and electric fields are suitable, sharp resolution of horizontal resistivity discontinuity is possible. Figure 2 shows an example of MT apparent resistivity profiles obtained by computer modeling of a two-dimensional low resistivity structure, resembling a section perpendicular to strike of a fault. When the electric field is measured at right-angles to the strike direction (H polarization). The apparent resistivity profile varies abruptly at the boundary of the structure, therefore, we can accurately determine the dimensions of the fault by this method.

Secondly, the existence of a low resistivity zone along a fault probably indicates that it is active. Noritomi (1981) compiled the resistivity structure of some active faults in Japan and pointed out the possibility of verifying whether the fault is active or not by features of the resistivity structure. The Electromagnetic Research Group for the Active Faults (1982) studied the resistivity structure of the Yamasaki Fault, which has high microearthquake seismicity and sometimes large earthquakes, and found a remarkably low resistivity belt along the fault. Similar low resistivity belts have also been found along other known active faults (Noritomi 1981, Handa & Sumitomo 1985). However, inactive faults do not have such low resistivity zones, the only resistivity contrast being that between two formations shifted by the fault. Nishimura *et al.* (1986a) showed even the Itoigawa–Shizuoka Tectonic Line, one of the largest geological faults in Japan, has no low resistivity zone in an inactive area.

The reason why an active fault has a low resistivity zone was suggested by the Electromagnetic Research Group for the Active Faults (1982). A fracture zone formed along an active fault usually contains artesian groundwater (Nishimura 1983, Nishimura & Nakagawa 1986) and often a water saturated clay fault gouge,

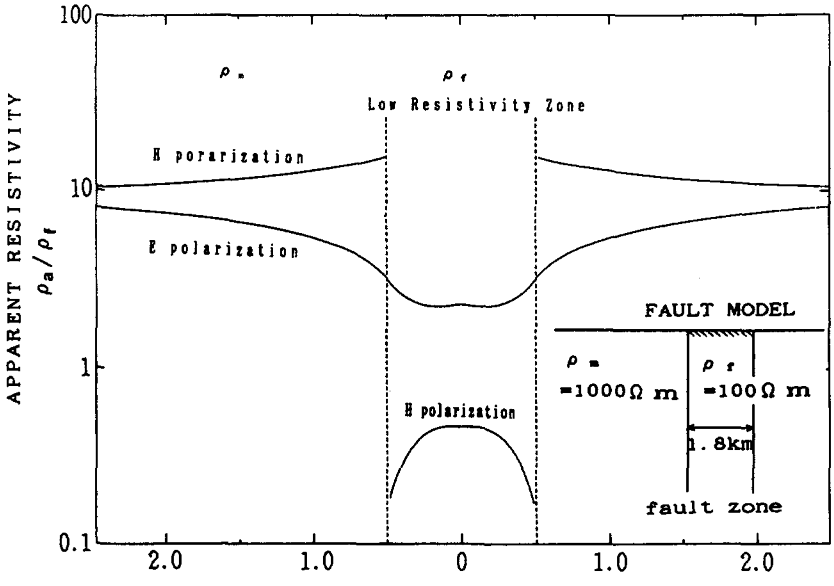

Fig. 2. Apparent resistivity profile for a fault model. The width of fault zone (low resistivity zone) is 1.8 km; r, distance; δ, skin depth of calculated frequency (8 Hz) for the medium; ρ_f, resistivity of fault zone; ρ_m, resistivity of medium.

features which would produce low resistivity within the active fault zone. When fault activity ceases, the water supply is reduced and dehydration occurs, thus reducing the water content of the materials and, hence, removing the low resistivity anomaly.

FIELD SURVEY IN THE NORTHERN PART OF KINKI DISTRICT

Active faults in the northern part of Kinki District were traced by a MT survey, in addition to a geological survey. The gamma-ray intensity and gravimetric data were also considered in this study. In this paper, the survey of the Yamasaki Fault and the Arima–Takatsuki Tectonic Line (ATL) area is described as an example (Fig. 3). Prior to the survey, there was a gap of 30 km between the eastern end of the Yamasaki Fault and the western end of the ATL. Geophysical and geological surveys were conducted between the extension area of these faults; Fig. 4 shows the results of the MT surveys. The telluric line was oriented perpendicular to the anticipated direction of the fault trace, and the magnetic component was measured parallel to it, so that the measured resistivity was the H polarization value. The resistivity section in this figure is obtained by matching the field values to calculated master curves of apparent resistivity against frequency for a layered structure. The limited measuring frequency restricts the vertical resolution of the resistivity structure, and the section (Fig. 4) shows only one or two layers. A low resistivity zone is found in both survey areas, with widths of 1–2 km. These resistivity structures are similar to the structure of the central part of the Yamasaki Fault (Handa & Sumitomo

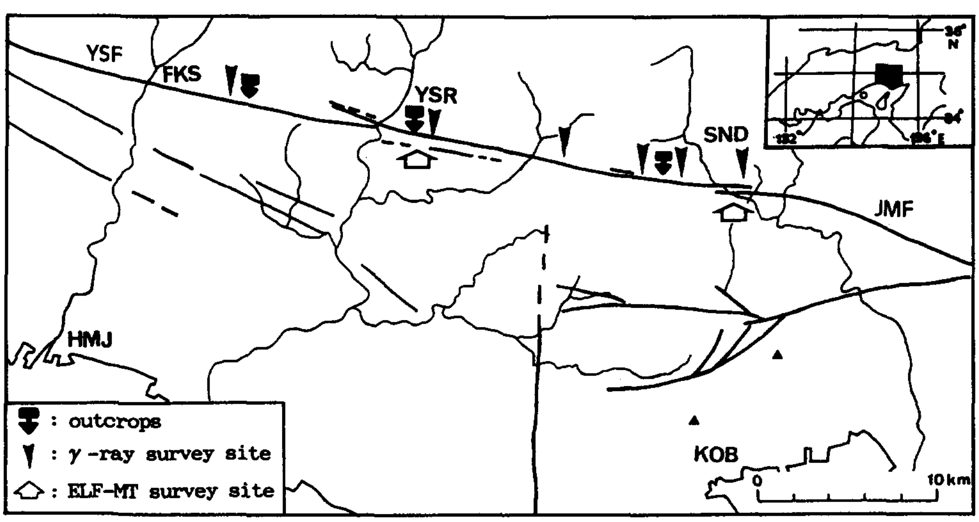

Fig. 3. Survey sites along the Yamasaki Fault and ATL area. YSF, Yamasaki Fault; JMF, Jumantsuji Fault (a member of ATL); YSR, Yashiro survey site; SND, Sanda survey site; KOB, Kobe City; HMJ, Himeji City; FKS, Fukusaki Town.

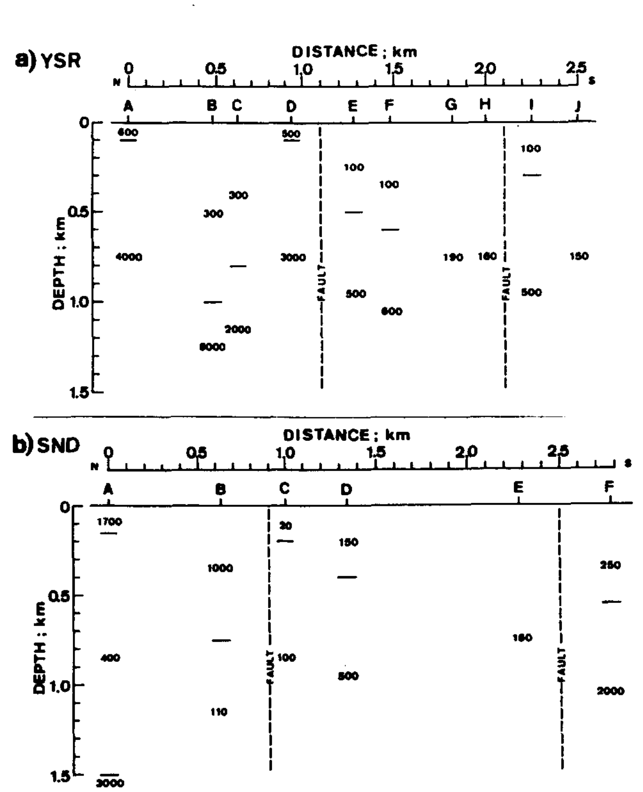

Fig. 4. The resistivity sections of (a) Yashiro and (b) Sanda area obtained by the magnetotelluric survey.

1985). Such a wide fault zone is caused by repeated active movements over a long period of time. From these results, we interpret a new active fault in this area joining the two previously known fault traces. The length of the composite large fault is now estimated at 120 km. The gamma-ray method also provided evidence of the existence of a fault in this area (Mogi *et al.* 1985b). Three outcrops of the fault were found in this area and ^{14}C dating of buried woods in the fracture zone, showed that the faults in this area moved in the last 3000 years (Nishimura *et al.* 1985). Similar surveys were conducted at the extension of other major faults: at the Mitoke, Yabu-Yagi, Yamada and Hanaori faults, and the western-end region of the Yamasaki Fault (Mogi *et al.* 1985a, Nishimura *et al.* 1986b, Katsura *et al.* 1987, 1989, Yamada *et al.* 1989). The results of these surveys (Fig. 5) show the distribution of large faults. These faults bound seven tectonic blocks which indicate different features of the distribution of active faults and earthquake occurrence, named as shown in Fig. 5. The Tanba Block is the most clearly defined one, whereas some of the external boundaries of other blocks have not been fully delineated.

TECTONIC ACTIVITY OF BLOCK

Boundaries of the tectonic blocks do not necessarily correspond to geological boundaries (Fig. 6), major faults sometimes running through geological units. Elsewhere they correspond to geological and topographical boundaries, the latter implying recent movement. In addition Hujita *et al.* (1973) have established that the present stress field has been continued and intensified since about 300,000 years ago.

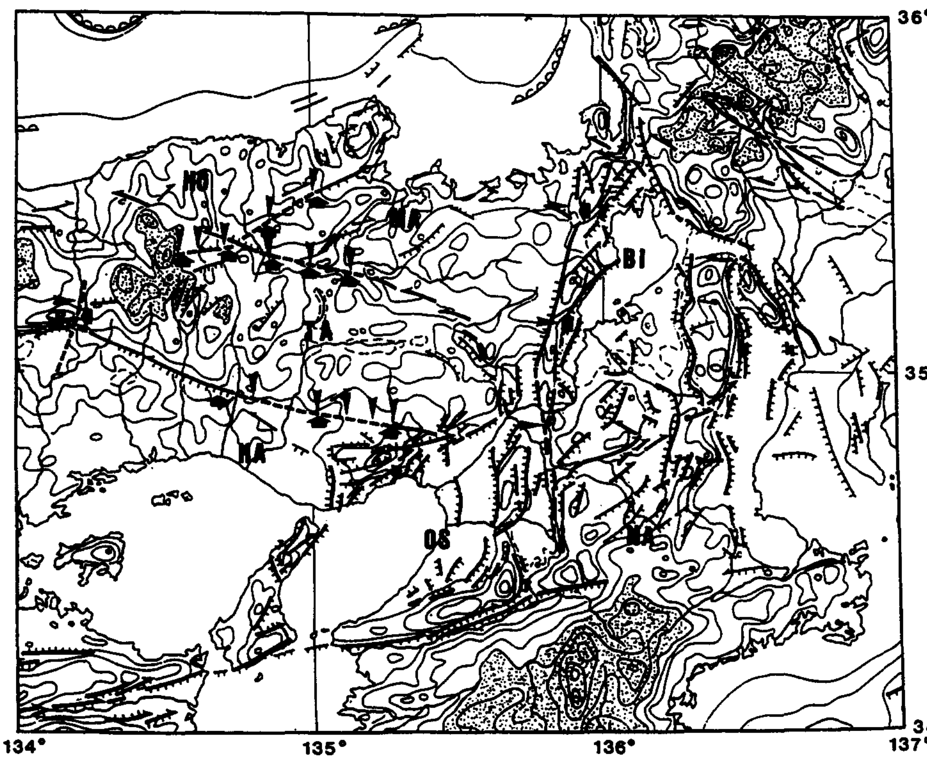

Fig. 5. Survey sites in the northern part of Kinki District. ▲: ELF–MT site, ▼: radioactive prospecting site. TA, Tanba Block; HO, Hokutan Block; MA, Maizuru Block; BI, Biwako Block; NA, Nara Block; OS, Osaka Block; HA, Harima Block. Dotted areas show high lands (more than 400 m high).

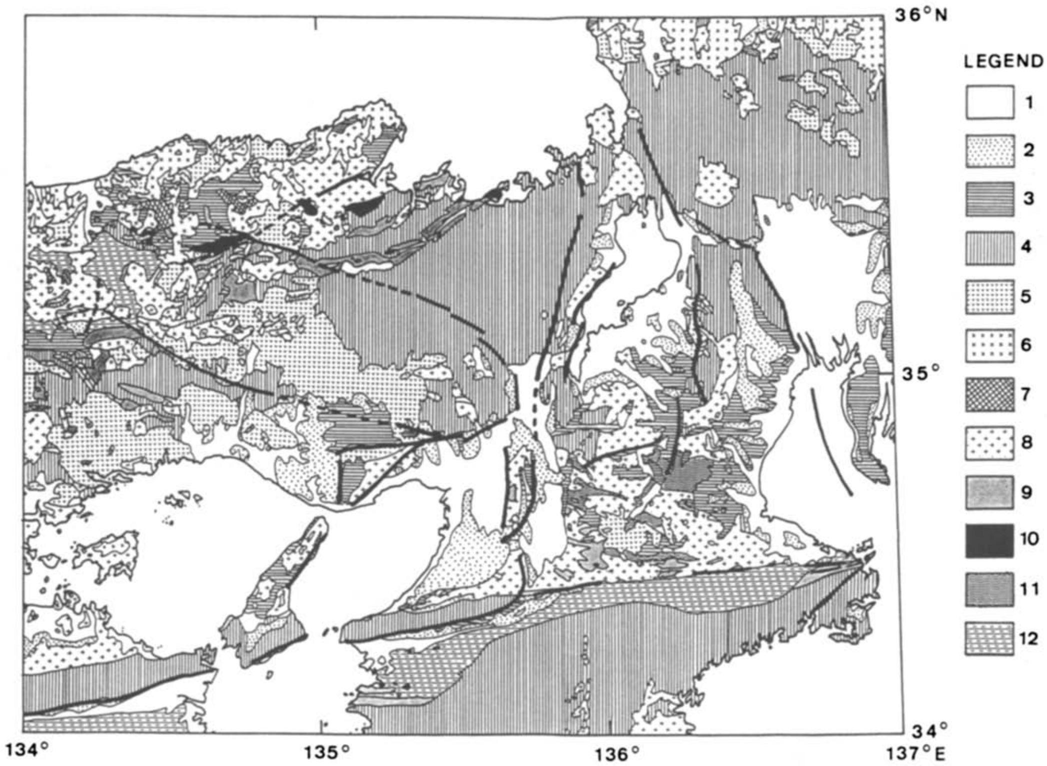

Fig. 6. Block structure and geological map (modified from Yamada *et al.* 1982). 1, Holocene sediments; 2, Pleistocene sedimentary rocks; 3, Neogene sedimentary rocks; 4, Pre-Neogene sedimentary rocks partly includes basalt; 5, rhyolite and dacites; 6, andesites and basalt; 7, alkali basalt; 8, granitic rocks; 9, gabbro and diorite; 10, ultramafic rocks; 11, low-pressure metamorphic rocks; 12, high-pressure metamorphic rocks.

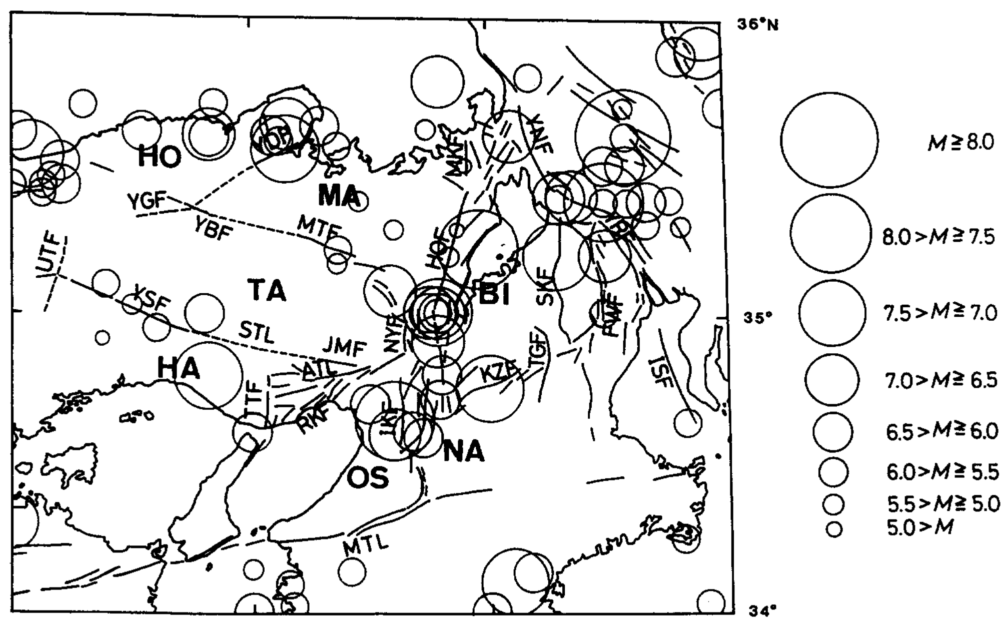

Fig. 7. Large earthquake (M>5) occurrence around the blocks. TA, Tanba Block; HO, Hokutan Block; MA, Maizuru Block; BI, Biwako Block; NA, Nara Block; OS, Osaka Block; HA, Harima Block; YSF, Yamasaki Fault; UTF, Ute Fault (new fault); STL, Sanda–Yamasaki Tectonic Line (new fault); YGF, Yagi Fault; YBF, Yabu Fault; MTF, Mitoke Fault; YDF, Yamada Fault; HOF, Hanaori Fault; MKF, Mikata Fault; YNF, Yanagese Fault; YRF, Yoro Fault; ISF, Ise Fault; FWF, Fujiwaradake Fault; SKF, Suzuka Fault; TGF, Tongu Fault; KZF, Kizugawa Fault; IKF, Ikoma Fault; NYF, Nishiyama Fault; ATL, Arima–Takatsuki Tectonic Line; RKF, Rokkou fault system; TTF Takatsukayama Fault; MTL, Median Tectonic Line.

Figure 1 shows the epicenters of microearthquakes, magnitude >2, depth <30 km, and the distribution of active faults. A large number of microearthquakes occurred in the Tanba Block, particularly in the eastern part, and there are many small NE–SW active faults. The activity of microearthquakes is generally high along the major faults, particularly the Yamasaki Fault. However, microearthquakes are scarce along the Yagi Fault. This distribution of seismicity may be caused by heterogeneity of the stress field applied to each block.

Figure 7 shows epicenters of large earthquakes, magnitude >5, which have occurred in the historical times, Many large earthquakes occurred on the northern side of this area. Moreover, large earthquakes occurred frequently at bends or intersecting points of large faults. This means that strain from the different stresses applied to each block appeared at the major faults in the form of occasional large earthquakes. Each tectonic block is a unit of the stress receiver in the crust. The size of the block probably having a close relation to the maximum magnitude of the earthquakes occurring within it.

CONCLUSION

Geophysical prospecting, especially the MT method, is valuable the mapping of active faults defining crustal blocks. These blocks, approximately 100 km wide, show a differing response to crustal stress. Crustal deformation generates earthquakes along the large faults at the boundary of each block. Therefore, understanding the block structure is very important to interpreting the tectonics of a district.

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