*Journal of Structural Geology*, Vol. 13, No. 2, pp. 227 to 233, 1991
Printed in Great Britain

0191-8141/91 $03.00+0.00


# Timing and displacement of Holocene faulting on the Median Tectonic Line in central Shikoku, southwest Japan

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(*Received* 21 *December* 1989; *accepted in revised form* 29 *May* 1990)

**Abstract**—The Median Tectonic Line (MTL) extends about 900 km parallel to the general trend of the southwest Japan island arc. The central segment of the MTL has been active during the Quaternary. Although the average slip-rate along the MTL is up to several mm $a^{-1}$, there is no historical record of destructive earthquakes along it. In order to collect data on the behavior of the MTL during late Holocene times, especially on the timing of seismic events and the amount of displacement during each event, trench studies were conducted on the active segment in central Shikoku in 1984 and 1988.

The results are summarized as follows: (1) the latest two seismic events produced by slip on the MTL in central Shikoku occurred during the early 8th century A.D., and between 3250 and 2820 years B.P.; (2) the amount of displacement during the latest event is inferred to have been about 5.7 m; (3) the earthquake magnitude for the latest event is estimated at 7.9 (Richter scale), and a fault-segment trace about 70 km long ruptured during that event; (4) an average slip-rate along the active trace of the MTL in central Shikoku during the late Quaternary is estimated to be 5–8 mm $a^{-1}$.

## INTRODUCTION

OBLIQUE subduction of the Philippine Sea plate beneath the Eurasian plate along the Nankai Trough results in mainly dextral transcurrent movement on the Median Tectonic Line (MTL) (Fitch 1972). The MTL, the most important geological break in southwest Japan, extends linearly ENE–WSW (Fig. 1). It divides southwest Japan into two parts; the inner belt to the north and the outer belt to the south. The central segment of the MTL, between central Kinki and western Shikoku, was active during the Quaternary with a predominantly right-lateral component of displacement. This active segment comprises a geologically distinct fault, as well as several parallel or en échelon active fault traces (Fig. 1).

Detailed field observations on the tectonic geomorphic features along the MTL revealed the average slip-rate to be several mm $a^{-1}$, which is one of the highest slip-rates known along active faults in Japan (Okada 1970, 1973a, 1980, Okada & Sangawa 1978). There is no historical record, however, of destructive earthquakes along the MTL. Paleoseismological data, especially on the timing of seismic events and the amount of displacement during each event, along the MTL in the past several thousands of years are essential for long-term earthquake prediction.

In Japan, trench studies have been conducted since 1978 on more than 20 faults to collect paleoseismic data. The main purpose of the studies has been to clarify the timing of seismic events rather than the amount of displacement per event and the average slip-rate. Data on displacement per event and average slip-rate, however, much improve long-term earthquake prediction (Schwartz & Coppersmith 1986).

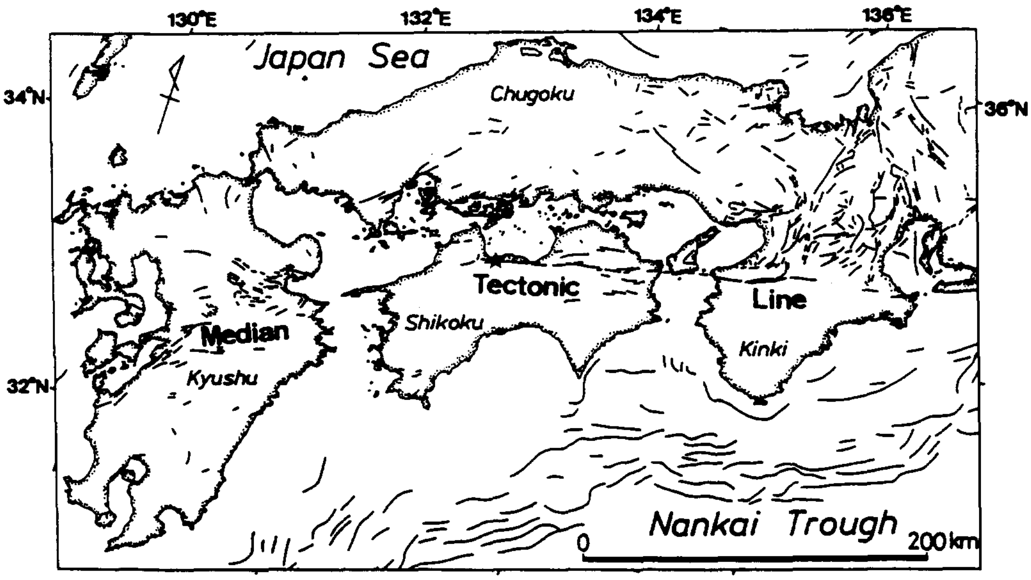


Fig. 1. Map showing active faults in southwest Japan. Active faults are shown by solid lines (after The Research Group for Active Faults 1980). Star shows the location of the trench site.

Trench studies were conducted on the Okamura fault, one of the active traces of the MTL, at Iyo-Saijyo City in central Shikoku. The aim was to determine the amount of horizontal displacement per event, as well as the timing of Holocene faulting.

The Okamura fault is situated 1.5 km north of the geologically distinct MTL. Around the trench site, the geologically distinct MTL is barely defined as an active fault, because none of the late Quaternary geomorphic surfaces are displaced along the fault. In contrast, the Okamura fault, parallel to the geologically distinct MTL, displaces late Quaternary geomorphic surfaces cumulatively with a predominant right-lateral component of displacement (Okada 1973b). The Okamura fault, therefore, has been much more active than the geologically distinct MTL during late Quaternary times. Paleoseismological data on the Okamura fault are considered to represent the contemporaneous behavior of the MTL.

Many of the phenomena associated with large earthquakes are generally well preserved in the sedimentary record. They include faults, folds, fissures and soft-sediment deformation. In order to maximize the chances of recording seismogenic events, we selected a trench site through the upper part of an alluvial fan. Two trenches were excavated across the active fault trace on the proximal part of present alluvial fan which is being formed by streams dissecting an early to Middle Pleistocene terrace. Radiocarbon dates were obtained from peats, humic soils and plant tissue. The dates for the 1984 trench were obtained from several radiocarbon-dating laboratories. All $^{14}C$ ages for the materials collected in the 1988 trench were obtained from the radiocarbon dating laboratory, Department of Geography, Hiroshima University, using the laboratory procedure described by Fujiwara & Nakata (1984) and Fujiwara *et al.* (1986). Several fragments of pottery were also collected in the trenches, and their ages were determined by Dr Shozo Tanabe, of the Kyoto College of Art.

## GEOMORPHOLOGY AND GEOLOGY AROUND THE TRENCH SITE

Right-lateral offsets of streams and tectonic bulges along the Okamura fault trace suggest a predominantly right-lateral component of displacement. Late Quaternary terraces are also cumulatively downthrown to the north. We excavated across the central segment of the Okamura fault at the foot of a small fault scarp that offsets a Pleistocene fluvial terrace. Though there is no topographic expression on the present alluvial fan, we predicted the location of the Okamura fault trace from the straight continuation of the small fault scarp.

The geology to the south of the trench site consists of Cretaceous Izumi Group (sandstone), Pliocene Okamura Formation (sandy silt with crystalline schist pebble), Quaternary middle terrace deposits (schist pebble–boulder plugged with sand) and Quaternary lower terrace deposits (sandstone pebble–cobble enriched with sand) (Fig. 2). Gravel beds in the Okamura Formation and the Quaternary middle terrace deposits consist of schist gravels derived from the Sanbagawa metamorphic rocks to the south of the geologically distinct MTL. Gravel beds, however, in the Quaternary lower terrace deposits consist of Izumi Group sandstone gravels. Valleys A, B and C (Fig. 2) supplied different kinds of gravels related to their headwater geology. Valley A mostly supplies schist gravels, valley B both schist and sandstone gravels, and valley C mainly sandstone gravels. Because the alluvial fan on which the trenches were excavated, comprises sediments derived from valley A, most of the sediments in the trenches contain schist gravels. A few horizons in the trenches contain

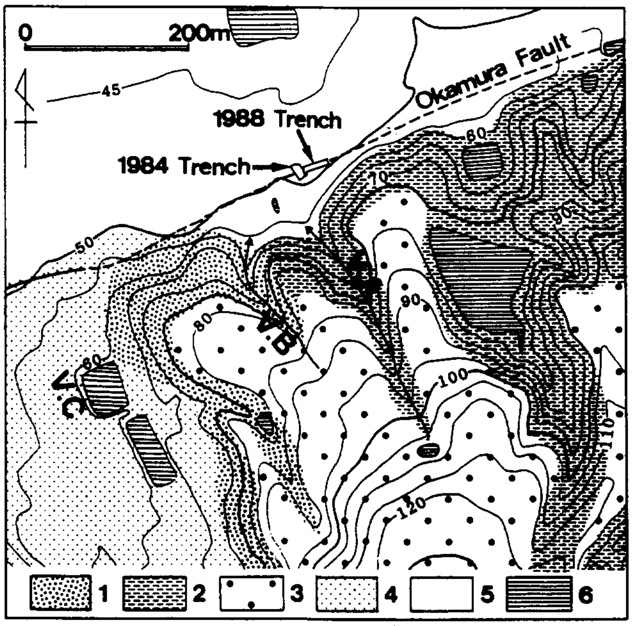


Fig. 2. Geologic map of the trench site area. Contours in metres are after the National Fundamental Map (scale: 1/5000, IV-GD 63, 64, Geographical Survey Institute). (1) Cretaceous Izumi Group (sandstone), (2) Pliocene Okamura Formation (sandy silt with schist pebble), (3) Quaternary middle terrace deposits (schist pebble–boulder plugged with sand), (4) Quaternary lower terrace deposits (sandstone pebble–cobble enriched with sand), (5) alluvium, (6) pond.

Table 1. $^{14}C$ ages in the 1984 trench

| Sample | $^{14}C$ ages (years B.P.) | |
|---|---|---|
| 1 | 12.160 ± 310 | (I—13750) |
| 2 | 3.360 ± 80 | (I—13595) |
| 3 | 2.940 ± 80 | (I—13594) |
| 4 | 8.570 ± 290 | (I—13599) |
| | 10.300 ± 120 | (KSU—792) |
| | 7.445 + 270 − 260 | (HR—052) |
| 5 | 9.990 ± 80 | (KSU—793) |
| | 9.760 + 395 − 375 | (HR—051) |
| 6 | 13.200 ± 380 | (KSU—783) |
| 7 | 2.900 ± 55 | (KSU—788) |
| 8 | 3.870 ± 85 | (KSU—785) |
| 9 | 2.025 ± 85 | (HR—053) |
| 10 | 29.000 ± 950 | (I—13600) |
| 11 | 17.800 ± 370 | (KSU—784) |
| 12 | 13.100 ± 120 | (KSU—787) |
| 13 | 11.530 ± 450 | (I—13598) |
| | 12.000 ± 80 | (KSU—787) |
| 14 | 11.200 ± 200 | (KSU—790) |
| 15 | 11.100 ± 260 | (KSU—786) |
| 16 | 1.920 ± 80 | (I—13597) |
| | 2.050 ± 55 | (KSU—791) |
| 17 | 1.440 ± 200 | (KSU—781) |

Parentheses show the laboratory code: I—Teledyne Isotopes, New Jersey, U.S.A.; KSU—Kyoto Sangyo University, Kyoto, Japan; HR—Hiroshima University, Hiroshima, Japan.

sandstone gravels, probably derived from valley B or C; they were used as key layers to estimate horizontal slip-rates.

## TRENCH STRATIGRAPHY

### 1984 *trench*

In March 1984, a trench was excavated, 21.6 m long (N–S), 11.3 m wide (E–W) and 5.7 m deep (Fig. 3a). The slope of the walls was 45°. The east and west walls on which the fault trace cropped out were studied in detail, and sketched at a scale of 1:25 and 1:10. All sediments, except for the artificial fill and the upper part of the cultivated soil, are clearly displaced by the fault which splays upwards into several branches, to form a 1-m-wide fault zone near the surface. The dip of the fault is more than 60°, though it appears to be gentler on the walls because the trace slants across the sloping trench walls.

The sediments in the trench are classified into five units based on facies, unconformities and $^{14}C$ ages (Fig. 3b). Unit I is a compact bluish-gray fine-sand bed containing round sandstone pebbles. This unit may have been derived from valley C and accumulated in front of the valley, then shifted to its present position by right-lateral slip. The unit dips north at 50° and is separated from Unit II by a clino-unconformity.

Unit II is a granule-pebble bed of schist clasts intercalated with fine–medium sand and humic soil layers. The lowermost humic soil on the west wall (10 in Fig. 3b) (Table 1), has a $^{14}C$ age of 29,000 ± 950 years B.P. This unit is underlain by a humic soil of 13,100 ± 120 years B.P. on the west wall (12 in Fig. 3b) (Table 1). Units I and II occur only on the northern side of the fault.

Unit III consists of well-bedded schist granules, fine–medium sand and humic soil layers. The unit is much disturbed by the fault and displaced with a south-side down component. In the lowermost part of this unit on the west wall (a in Fig. 3b), sandstone pebbles occur with schist pebbles. This unit may have been derived from valley B. There appear to be no sediments dated between 7000 and 4000 years B.P.

Unit IV contains poorly sorted schist pebbles intercalated with humic soil layers. The unit is much thicker on the southern side than the northern side of the fault. The uppermost humic soil in this unit on the west wall (16 in Fig. 3b) (Table 1), yields $^{14}C$ ages of about 2000 years B.P.

Unit V is a cultivated soil and artificial fill bed. The lower part of the cultivated soil on the west wall is dragged along the fault (b in Fig. 3b), and appears to have filled the crack associated with the latest event. Three pieces of pottery were collected in this part, and two pieces were dated as post-middle-4th century A.D., and the remainder was dated as post-8th century A.D.

### 1988 *trench*

The 1988 trench was excavated to the east of the 1984 trench. The trench is 35 m long (E–W), 7.6 m wide (N–S) and 2.5 m deep (Fig. 4a). We first excavated parallel trenches on both sides of the fault trace in order to obtain evidence for horizontal displacement. Seven N–

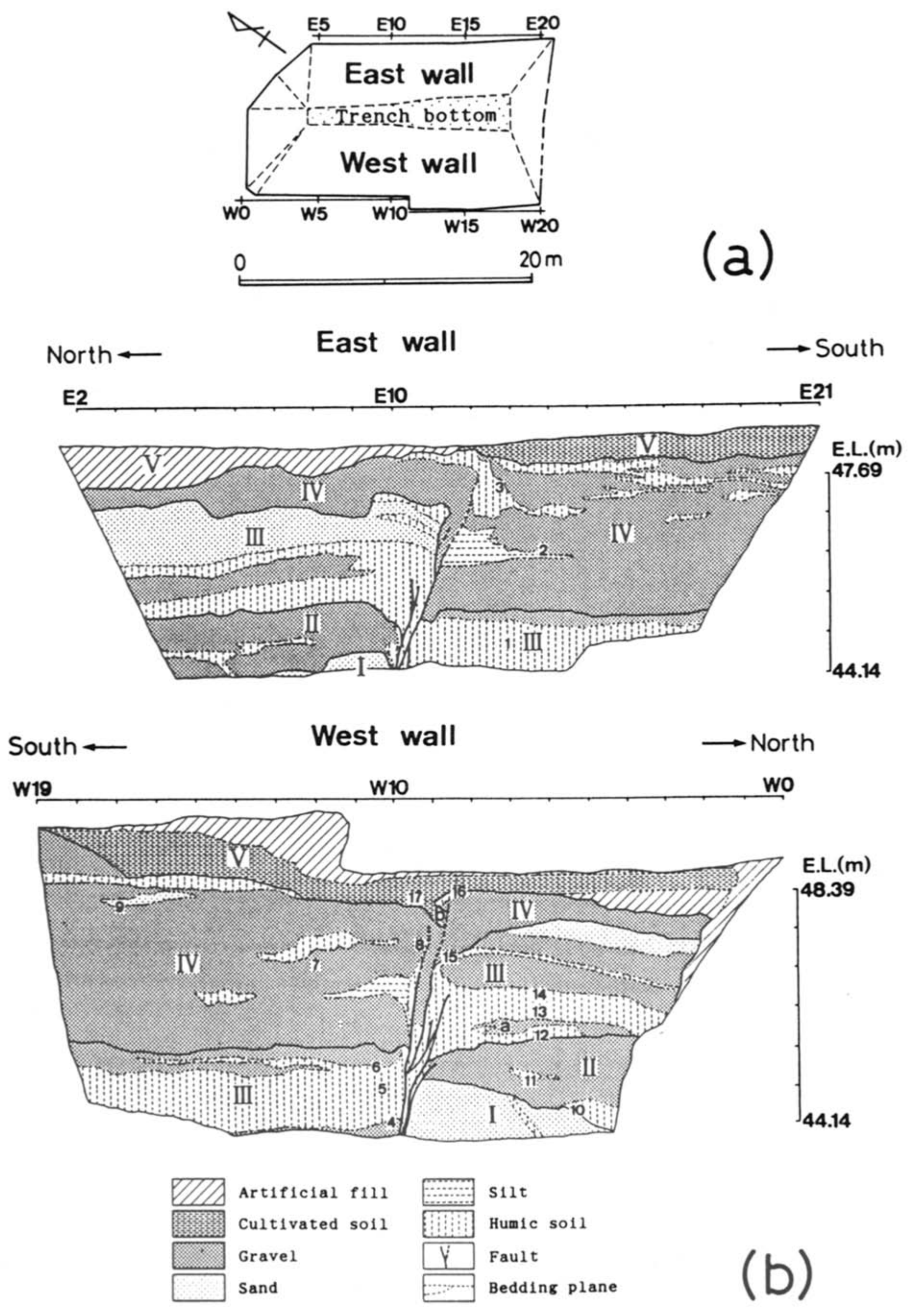


Fig. 3. Simplified sketches of the 1984 trench. (a) Plan of the trench. Numerals on the east and west walls are grid numbers. (b) Simplified profiles of the east and west wall in the 1984 trench showing lithologies, stratal boundaries, the fault zone and classification into units. See the text for explanation. Numerals show locations of samples for radiocarbon dating (see Table 1).

S-trending trenches were then cut across the fault, and were designated trenches A–G from east to west. Each trench has east and west walls for observation; A–E, A–W, etc. (Fig. 4a). The slope of the walls is almost vertical, except for A–E and A–W walls which sloped at 45°. The walls were sketched at a scale of 1:10. The fault displaces all sediments except for the uppermost cultivated soil. The sediments were classified as shown in Figs. 4(a) & (b), based on facies, unconformities and $^{14}C$ ages.

The older humic silt (OH) is a compact brownish silt bed containing plant tissue. This unit is divided into three beds; the upper bed (OHu), the middle bed (OHm) and the lower bed (OHl). A $^{14}C$ age of 11,700 + 520 − 490 years B.P. was obtained for the OHu and 14,690 + 430 − 410 years B.P. for the OHm. Below the OHm bed on the A–W wall, there is a coarse-sand bed containing sandstone and schist pebbles. This bed is inferred to have been derived from valley B. Sediments dated between 11,000 and 4000 years B.P. do not occur in the trench.

The younger sandy silt (YSS) is interbedded between the OHu bed and the younger humic silt (YHS) on the northern side of the fault. This unit thins to the east, from 2 m thick on the G–E wall to 1 m on the A–W wall. Five $^{14}C$ ages between 3330 ± 180 and 2770 + 200 − 190 years B.P. were obtained for this unit.

The younger gravel (YG) is a poorly sorted schist

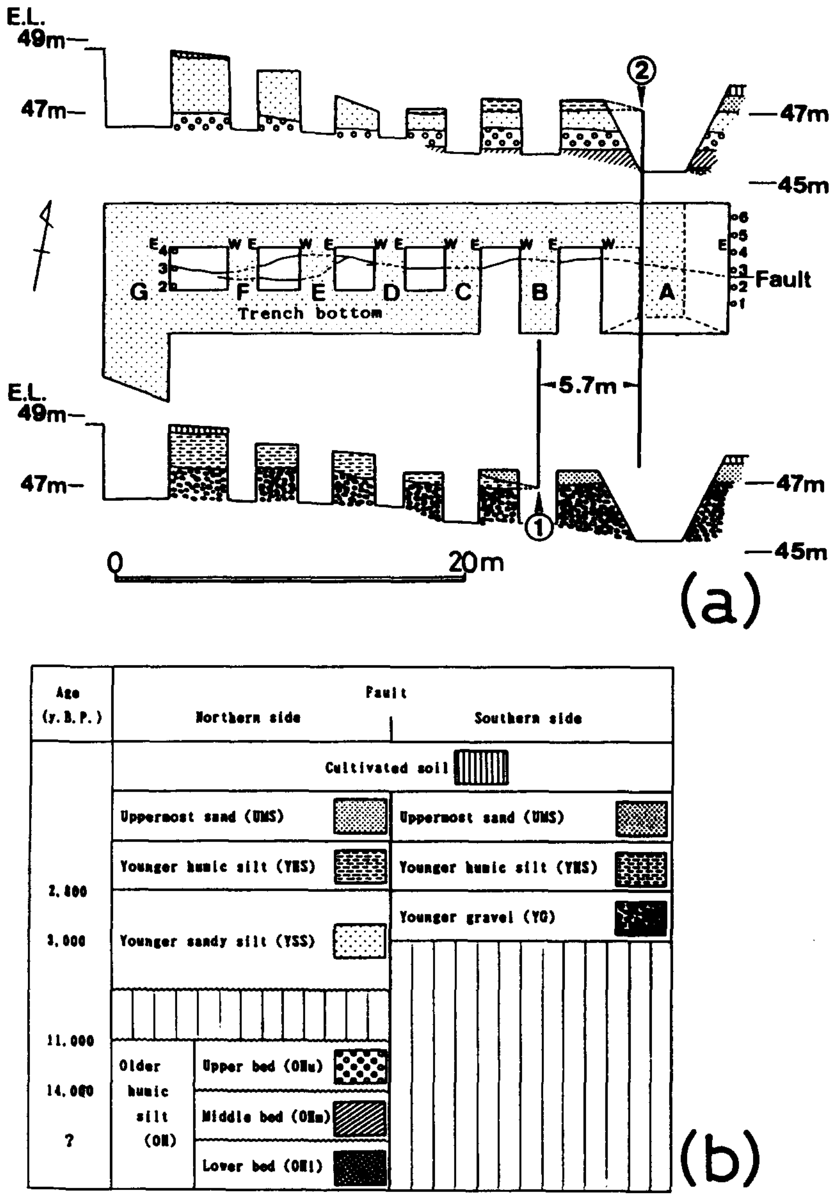


Fig. 4. Classification of deposits in the 1988 trench. (a) Plan and profiles showing classification of deposits and restoration of horizontal displacement for event 1. Legend as in part (b). ① shows the terminating point of the YHS on the southern side of the fault. ② shows the terminating point of the YHS on the northern side of the fault. (b) Classification of deposits in the 1988 trench. Wavy line shows unconformity. See text for explanation.

pebble–cobble bed with intercalated humic soil layers on the southern side of the fault. The humic soil layers contain fragments of leaves, branches and seeds of oak trees. The unit is underlain by the younger humic silt (YHS) between the G–E and B–W walls, and by the uppermost sand (UMS) between the B–E and A–E walls. Five $^{14}C$ ages for this unit are between 3220 + 460 − 440 and 2940 + 250 − 240 years B.P.

The younger humic silt (YHS) is a brownish humic silt bed which thins to the east. On the southern side of the fault, the YHS is 90 cm thick on the G–E wall, 50 cm thick on the C–E wall, 20 cm thick on the B–W wall and absent on the B–E wall. On the northern side of the fault, the YHS is observed between the A–W and D–E walls.

The uppermost sand (UMS) is a grayish-white fine-sand to silt bed, and occurs along the eastern part of the trench. On the southern side of the fault, this unit overlies the YG on the A–E, A–W and B–E walls, and the YHS on the B–W and C–E walls. On the northern side of the fault, the unit is observed only on the A–E wall overlying the YSS.

## LATE HOLOCENE SEISMIC HISTORY

### *Timing of seismic events*

Fifteen fault traces in the two trenches were examined in detail to identify geological evidence for large seismic events produced by slip on the active trace of the MTL in central Shikoku during the Holocene. The principal indicators of past seismogenic events are: (1) the termination of secondary faults at distinct levels within the

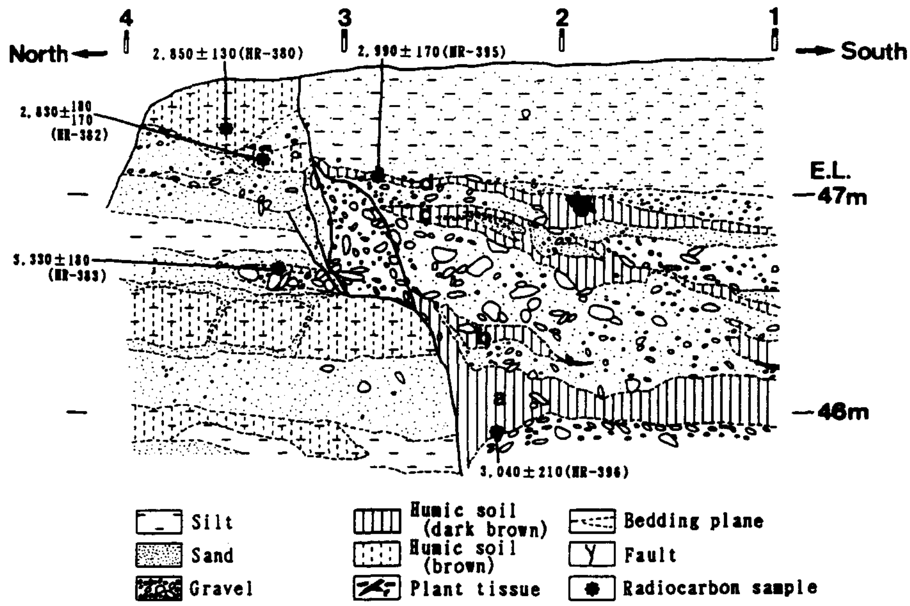


Fig. 5. Sketch of the B–E wall in the 1988 trench showing lithologies, stratal boundaries, fault and $^{14}C$ ages. All $^{14}C$ ages were obtained from Hiroshima University.

Table 2. Estimation of average slip-rate on the Okamura fault during the late Quaternary

| Name of trench | Horizon containing sandstone gravels | Age (years B.P.) | Source of the sediments | Distance from the source (m) | Average slip-rate (mm $a^{-1}$) |
|---|---|---|---|---|---|
| 1984 | Lower part of Unit III | 12,000 ~ 13,000 | Valley B | *ca* 70 | 5.38 ~ 5.83 |
| 1988 | Between the OHm and OHl bed | Older than 14,700 | Valley B | *ca* 100 | ~ 6.80 |
| 1984 | Unit I | Older than 29,000 | Valley C | *ca* 230 | ~ 7.93 |

stratigraphic section, and (2) the variable displacement of each sedimentary unit across the main fault. These indicators and radiocarbon dates suggest that evidence for two seismic events emerge from the trench studies. We first discuss the data for the 1988 trench in which two events are recognized. For the 1984 trench we can determine precisely the timing of the latest event.

The latest event (event 1) took place at the level between the UMS and cultivated soil in the 1988 trench, because all sediments except for the cultivated soil have been displaced by the fault. A fragment of pottery was found in the YHS on the F–W wall, and is dated as post-4th century A.D. Event 1, therefore, occurred after the 4th century A.D.

Geological evidence for event 2 is recognized on the B–E (Fig. 5) and G–E walls. Two humic soil layers ( a and b) on the southern side of the fault on the B–E wall are dislocated and upturned. The upper humic soil layers (c and d) have not been dislocated as much as layers (a) and (b), though they are cut by the fault (Fig. 5). We, therefore, recognize event 2 at the level between the (a) and (b) layers and the (c) and (d) layers. $^{14}C$ ages suggest that event 2 occurred between 3040 ± 210 (age of the lowermost part of layer a) and 2990 ± 170 years B.P. (age of layer d). A similar indicator occurs on the G–E wall and $^{14}C$ ages suggest the timing of event 2 between 2940 + 250 − 240 and 3050 ± 180 years B.P. Synthesizing this data, we estimate the timing of event 2 between 3250 and 2820 years B.P.

It was not possible to identify any geological evidence of earthquakes prior to event 2, because sediments between 11,000 and 4000 years B.P. are absent in the 1988 trench.

In the 1984 trench, event 1 is recognized within the cultivated soil horizon. The lower part of this unit is disturbed by the fault (b in Fig. 3b). One of the three pieces of pottery contained in this part, gives an age of post-8th century A.D. Although historic records of destructive earthquakes in Japan appear to have increased abruptly since the Nara era (710–784 A.D.), no destructive earthquakes have been recorded along the MTL in central Shikoku (Usami 1987). We, therefore, estimate that event 1 occurred during the early 8th century A.D. In the 1984 trench, there is geological evidence for earthquakes prior to event 1, during the past several thousands of years, but $^{14}C$ dates are not enough for determining these events.

*Amount of displacement during event* 1

The amount of displacement during event 1 was estimated by the offset of the YHS layer on both sides of the fault in the 1988 trench (Fig. 4a). The YHS is displaced only by event 1. As mentioned above, the YHS thins to the east and terminates between the B–E and B–W walls on the southern side of the fault, and between the A–E and A–W walls on the northern side of the fault. The amount of displacement during event 1 is, as estimated from the offset of the YHS layer across the fault, between 2.4 m (i.e. the distance between the A–W and B–E walls) and 11.8 m (the distance between the A–E and B–W walls). In order to obtain the exact amount of displacement, the terminating points of the YHS have to be restored, based on the thickness of the YHS on the walls. The YHS is 50 cm thick on the C–E wall, 20 cm thick on the B–W wall and absent on the B–E wall on the southern side of the fault. It is 30 cm thick on the B–W and A–W walls and absent on the A–E wall on the northern side of the fault. If the YHS on the northern side of the fault thins to the east from the A–W wall in the same ratio as on the south of the fault, 5.7 m of right-lateral displacement is estimated to have occurred during event 1. No vertical displacement is recognizable for event 1 from the height of the bottom of the YHS across the fault.

*Magnitude and fault length of event* 1

The displacement ($D$) accompanying an earthquake has an empirical relation to the earthquake magnitude (**M**) (Richter scale) as

$$\log D(\mathrm{m}) = 0.6\mathbf{M} - 4.0 \qquad (1)$$

for Japanese inland earthquakes. The relation of fault length ($L$) to **M** is also empirically formulated as

$$\log L(\mathrm{km}) = 0.6\mathbf{M} - 2.9 \qquad (2)$$

(Matsuda 1975). If we take a 5.7 m lateral offset as the displacement during event 1 and substitute this amount in equation (1), an earthquake of magnitude 7.9 is estimated for event 1. Substituting this magnitude in equation (2), faults about 70 km long are considered to have been active during event 1. The length of the Okamura fault is only 20 km, while the total length of the active traces of the MTL in central Shikoku is 60 km. It is, therefore, inferred that the entire length of the MTL in central Shikoku may have moved during event 1.

*Average slip-rate during the late Quaternary*

Only three horizons containing the Izumi Group sandstone gravels were found in the trenches. The sandstone gravels were derived from valleys B or C, which originated from the Izumi Group terrain and subsequently migrated to their present position by right-lateral slip. Based on the age and distance from the source for each horizon, average slip-rates during the late Quaternary were calculated (Table 2). Synthesizing the data contained in the table, an average slip-rate of 5–8 mm $a^{-1}$ is estimated for the Okamura fault, that is, the active trace of the MTL in central Shikoku. This average slip-rate is comparable to those of transcurrent faults which are located on other island arcs elsewhere in the world; that is, 1.5–5 mm $a^{-1}$ for the Philippine fault zone (Hirano *et al.* 1986) and 5–7 mm $a^{-1}$ for the Great Sumatran fault zone, Indonesia (Katili & Hehuwat 1967).

*Acknowledgements*—We collaborated on the trench studies with the Japan Highway Public Corporation. We are grateful to Shozo Tanabe, Kyoto College of Art for his determining the ages of pottery fragments.

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