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Depositional Age of Event Sand Layers Apparent in Upper Holocene Sequence Across the Kuwana Fault, Southwestern Nobi Plain, Central Japan

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Abstract In the regional settings, where tsunami can be caused by not only ocean-trench earthquakes but also faulting on the submarine active faults, identification of event deposits suggesting strong stream and age estimation of these deposits is important for accurate evaluation of paleosesimicity in the coastal area. The Kuwana fault is located on southwestern part of the Nobi Plain, central Japan. This reverse fault displaces a late Pleistocene terrace surface with 1 to 2 mm/yr of average vertical slip rate, and a topset of delta at several meters, respectively. And, this fault is estimated to have generated multiple earthquakes including two historical earthquakes (the AD 745 Tempyo and the AD 1586 Tensho earthquakes) during the Holocene. We identified two event sand layers from upper Holocene shallow marine sediments on the upthrown side of the Kuwana fault. Lower sand layer shows upward-coarsening succession, whereas upper sand layer upward-fining succession. These sand layers contain sharp contact, rip-up crust, and shell fragment, indicating strong stream. Cause of strong stream can be tsunami by the faulting on the sea-floor located active fault, storm, or flood. Although determination of the cause of these two strong stream events is difficult at this moment, radiocarbon ages show that these strong stream events occurred between 3,000 and 1,600 years ago. More detail chronological constraint of these event deposits and correlation with paleoseismicity in this region is future subjects.

Key words : 14C-AMS, Kuwana fault, Holocene, sediment core, event deposits

1. Introduction

On-fault paleoseismological studies, such as trench surveys, is useful for understand detailed records of the timing and magnitude of past fault activity (e.g., Machette et al., 1992 ; Liu et al., 2006). However, Identification of paleoseismic events on the basis of on-fault paleoseismology is difficult if submarine and concealed active fault is targeted at. Thus, to clarify

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and precisely reconstruct paleoseismicity, we have to focus attentions on some kind of paleoseismic evidences in addition to on-fault paleoseismic evidences.

Tsunami deposit is one of the useful paleoseismic evidences (e.g. Umitsu, 1999 ; Fujiwara et al., 2004). By using tsunami deposits, earthquake history, especially ocean-trench earthquake, is evaluated on the coastal area (e.g. Atwater, 1987 ; Williams and Hutchinson, 2000 ; Jankaew et al., 2008). In the regional settings, where tsunami can be caused by not only ocean-trench earthquakes but also faulting on the submarine active faults, if depositional age of event deposits, one of the cause of which is tsunami, is estimated, paleoseismicity can be understood with high accuracy.

The Kuwana fault (Figure 1) is suggested to have generated multiple large earthquakes including two historical earthquakes, the AD 745 Tempyo (Usami, 1996) and AD 1586 Tensho (Iida, 1987) earthquakes, on the basis of vertical offset of shallow marine sediments (Sugai et al., 1998a ; Sugai, 2011 ; Naruhashi et al., 2004, 2008). Faulting on this fault can cause tsunami when the fault is located on the sea-floor. In addition, the evidence may be recorded in

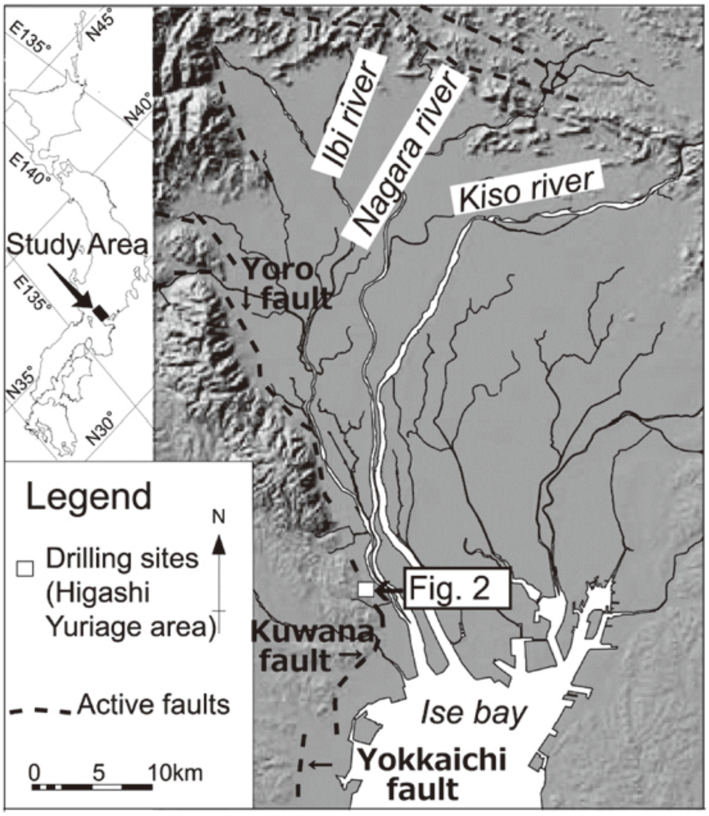

Figure 1 Study area

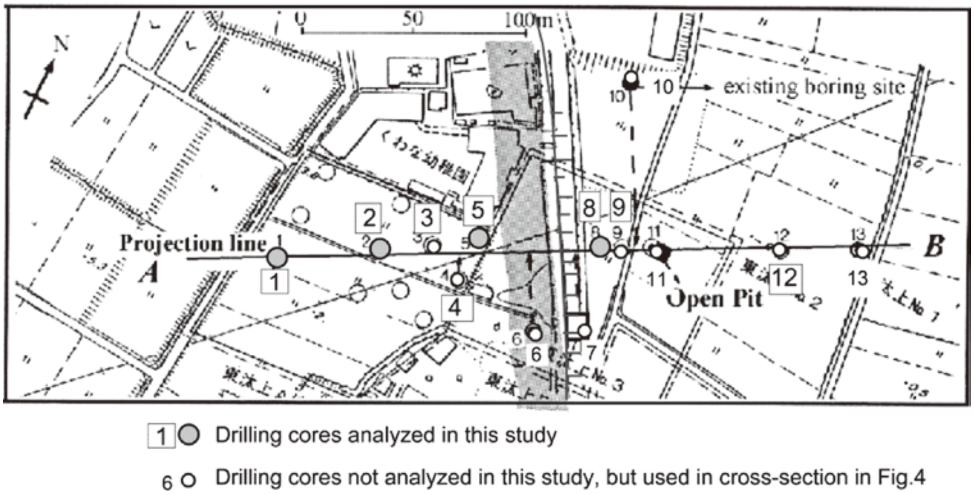

Figure 2 Location of drilling cores used in this study

the shallow marine sediments as tsunami deposits.

In this background, we re-examined shallow marine sediments across the Kuwana fault, which was used for on-fault paleoseismological study (Figure 2 ; Sugai et al., 1998a, b) on the view of identification of tsunami deposits and age estimation. We identified two event sand layers suggesting strong stream events, although the cause of these two strong stream events is not clear at this moment. And, we estimated timing of these events based on radiocarbon datings.

2. Regional Setting

2.1. The Yoro fault system

The Yoro, Kuwana, and Yokkaichi faults (hereafter The Yoro fault system) lies at the western margin of the Nobi Plain with a combined length of about 55 km (Research Group for Active Faults of Japan, 1991 ; Sugai et al., 1999 ; Ikeda et al., 2002 ; Figure 1). The Yoro fault system forms the geomorphic and geologic western boundary between the Nobi Plain with more than 1,500 m of Neocene and Quaternary strata (Sugai and Sugiyama, 1998) and the Yoro mountains which consist of the Mesozoic and Paleozoic sedimentary rocks (Takada et al., 1979).

Activity on the Yoro fault system has been reconstructed based on vertical offsets of depositional surfaces in shallow marine sediments. The Yoro and Kuwana faults are suggested to have generated both the AD 745 Tempyo (Usami, 1996) and AD 1586 Tensho (Iida, 1987) earthquakes (Sugai et al., 1998a ; Sugai, 2011). Detailed analyses of changes of the accumulation rate of shallow marine sediments indicate that the Kuwana fault has been active five times between 7,000 and 2,000 years ago (Naruhashi et al., 2004, 2008). Even though the Yokkaichi fault has a right-stepping relationship to the Kuwana fault (Figure 1), both the pattern of accumulation of vertical displacement during the past 7,000 years and the timing of the last three faultings on the Yokkaichi fault agree well with those of the Kuwana fault (Ogami and Sugai, 2006).

In addition with these on-fault paleoseismological studies, faulting history of the Yoro fault system has been reconstructed by using evidences which can be recorded at locations distant from the earthquake source (Niwa et al., 2009, 2012). These off-fault paleoseismic studies detected four or five coseismic subsidence events caused by faulting on the Yoro fault and provided further evidence of faulting events inferred from the on-fault paleoseismic studies that the Yoro and Kuwana faults have generated large earthquakes synchronously and that comprised a behavioral segment within the Yoro fault system.

2.2. The Nobi Plain

The Nobi Plain tilts down to the west as a result of activity on the Yoro fault system (Kuwahara, 1968). Tilting and subsiding rates are 0.86×10^{-4}/ka and 1 m/ka, respectively, in the southwestern Nobi plain (Sugai and Sugiyama, 1999). Holocene deposits are thick on the plain because of not only this high subsidence rate, but also postglacial marine transgression and huge amounts of sediment supplied by the Kiso River from the central mountain range of Japan, which has the world's highest denudation rate (Ohmori, 1983). There are several previous studies of the stratigraphy and sedimentary facies of the latest Pleistocene-Holocene deposits of the Nobi Plain, focusing attentions on reconstruction of the depositional environment and process of delta formation (Iseki, 1962 ; Umitsu, 1992 ; Masuda and Iwabuchi, 2003 ; Yamaguchi et al., 2003 ; Ogami et al., 2009). The latest Pleistocene-Holocene sequence was divided into five sedimentary units : 1) braided river deposits, 2) fluvial to intertidal deposits, 3) inner bay to prodelta deposits, 4) delta front deposits, and 5) delta plain and fluvial deposits, in ascending order (Yamaguchi et al., 2003 ; Ogami et al., 2009).

3. Materials and Methods

Four sediment cores (HYR-1, 2, 5, 8 ; Figure 2) across the Kuwana fault were used in this study. These cores are located southwestern (downstream) part of the Nobi plain. Thus, cores show prograding delta sequence (Sugai et al., 1998a). We undertook lithofacies and grain-size analyses, performed electrical conductivity (EC) measurements, and obtained radiocarbon ages for sediments.

For these cores, we also described sedimentary structures in the cores and the existence or nonexistence of bioturbation, shells, and plant fragments. We measured grain size at depth intervals of 5 to 10 cm by using a laser diffraction particle-size analyzer (SALD-3000S ; Shimadzu Corporation, Kyoto, Japan). The sediment samples used for these analyses were selected from the parts of the core that showed typical lithofacies without bioturbation.

We measured EC at depth intervals of 5 to 200 cm. The method of EC measurement is based on Yokoyama and Sato (1987). The method is described below. Samples were first parched at 110°C for 48 h and then milled in a vibrating sample mill (TI-100 ; CMT Co. Ltd, Tokyo, Japan). Then, 5 g of each sample was stirred with 60 ml of distilled water in a sample vial. The samples were stored at room temperature for 7 days in the laboratory after which EC was measured with a conductivity meter (Cond Meter ES-51 ; Horiba, Kyoto, Japan).

A total of 17 radiocarbon ages were obtained from fossil molluscan shells and wood fragments by accelerator mass spectrometry (AMS) in Micro Analysis Laboratory, Tandem accelerator (MALT), The University of Tokyo. Calendar years were calibrated using Calib version 6.0 software (Stuiver and Reimer, 1993). MARINE13 calibration curves (Reimer et al., 2013) were used for fossil molluscan shells and INTCAL13 calibration curves (Reimer et al., 2013) for wood fragments. Because the local reservoir effect for marine samples has not been deter-

Table 1 Results of radiocarbon dating

Sample Name	Lab Code	Material	Depth (cm)	Altitude (cm)	Conventional Age (years BP)	Calibrated Age (2σ cal years BP)	δ13C (‰)
HYR01-0143	MTC-13552	Shell	143-151	105-113	2,082±45	1,535-1,785	−5.62
HYR01-0185	MTC-11755	Shell	185	71	2,004±33	1,479-1,681	−3.03
HYR01-0310	MTC-11756	Shell	310	−54	1,985±41	1,419-1,669	−1.53
HYR01-0371	MTC-11757	Shell	371	−115	2,675±34	2,291-2,477	−2.27
HYR01-0449	MTC-11758	Shell	449	−193	2,968±35	2,685-2,829	−0.04
HYR02-0144	MTC-11750	Shell	144	100	2,191±31	1,697-1,872	−3.76
HYR02-0474	MTC-11754	Shell	474	−230	3,386±110	2,942-3,509	−0.81
*HYR05-0025	Beta-114639	Organic sediments	25	210	840±70	673-911	−28.6
*HYR05-0048	Beta-118209	Plant material	48	187	1,960±60	1,769-2,056	−23.7
*HYR05-0178	Beta-114640	Plant material	178	57	1,390±60	1,226-1,404	−25.6
*HYR05-0178	Beta-114641	Shell	178	57	1,850±50	1,291-1,510	−1.00
*HYR05-0248	Beta-114642	Organic sediments	248	−13	3,150±80	3,200-3,566	−25.30
HYR05-0474	MTC-11743	Shell	474	−239	3,088±40	2,751-2,968	−0.75
*HYR05-0488	Beta-118210	Organic sediments	488	−253	4,310±120	4,569-5,291	−25.60
*HYR08-0065	Beta-114106	Organic sediments	65	−87	2,260±60	2,120-2,358	−26.50
*HYR08-0065	Beta-114532	Plant material	65	−87	880±50	698-916	−31.40
*HYR08-0245	Beta-114107	Plant material	245	−267	1,520±50	1,317-1,522	−27.30
HYR08-0264	MTC-14157	Wood	264	−286	1,709±46	1,523-1,722	−29.36
*HYR08-0370	Beta-114108	Organic sediments	370	−392	3,070±80	3,061-3,450	−26.60
HYR08-0444	MTC-13556	Shell	444	−466	2,107±46	1,557-1,812	3.19
HYR08-0651	MTC-14153	Wood	651	−673	2,608±50	2,694-2,845	−38.79
HYR08-0688	MTC-13200	Shell	688	−710	3,191±61	2,830-3,089	9.78
HYR08-0796	MTC-13204	Shell	796	−818	3,787±54	3,577-3,873	−6.06
HYR08-0861	MTC-13202	Shell	861	−883	4,158±56	4,074-4,400	−1.47
HYR08-0960	MTC-13203	Shell	960	−982	4,426±72	4,415-4,796	−6.83

*^{14}C ages by Sugai et al. (1998a, b)

mined for this area, we defined ΔR to be 0, adopting the approach used in recent studies in this area (e.g., Naruhashi et al., 2008). Radiocarbon ages obtained not only in this study but also in Sugai et al. (1998a, b) are shown in Table 1 as calendar years before present (AD 1950 datum).

4. Sedimentary facies and depositional environment

Sedimentary units were identified and their depositional environments interpreted based on lithofacies and EC (Figure 3). Following the interpretation of Niwa et al. (2011), which was based on a comparison of EC with the results of facies and diatom analysis, we interpreted EC lower than 0.4 mS/cm to represent a fresh water environment, EC between 0.4 and 0.9 mS/cm a brackish environment, and EC higher than 0.9 mS/cm a marine environment. Core description and unit segmentation of HYR-1, 2, 5, 8 is shown below.

Prodelta deposits (core depths : HYR-1, 5.00-4.52 m ; HYR-2, 5.00-4.60 m ; HYR-5, 5.00-4.80 m ; HYR-8, 10-7.30 m)

This facies (PD in Figure 3) comprises structureless mud of median grain size of finer than 6 φ. It contains marine shells and burrows, and EC is higher than 1.1 mS/cm.

This facies was interpreted as prodelta mud by Sugai et al. (1998a) on the basis of its fine and homogeneous grains and marine shells. This interpretation is supported by EC greater than 1.1 mS/cm, which suggests a marine environment. The sediments were dated at 2,685-2,829 cal BP (core HYR-1), 2,942-3,509 cal BP (core HYR-2), and 4,415-4,796～3,577-3,873 cal BP (core HYR-8).

Delta front deposits (core depths : HYR-1, 4.47-0.13 m ; HYR-2, 4.60-0.28 m ; HYR-5, 4.80-0.64 m ; HYR-8, 7.30-1.54 m)

The delta front facies (DF in Figure 3) coarsens upward from sandy silt to sand. The boundary with the underlying prodelta mud facies is sharp but not erosional. Median grain size changes upward from 6 φ to 1 φ. Bioturbation is apparent in the lower to middle part of this facies, whereas plant fragments and cross laminations are apparent in the middle to upper part. EC is 0.1-1.9 mS/cm in core HYR-1, 0.05-2.5 mS/cm in core HYR-2, 0.05-2.2 in core HYR-5, and 0.1-2.6 mS/cm in core HYR-8. This facies was previously interpreted as delta front deposits (Sugai et al., 1998a) because it conformably overlies prodelta mud facies and coarsens upward. The sediments were dated at 2,291-2,477～1,419-1,669 cal BP (core HYR-1), 1,697-1,872 cal BP (core HYR-2), 2,751-2,968 (core HYR-5), and 2,830-3,189～1,317-1,522 cal BP (core HYR-8). Two sand layers and shell fragment rich mud layer are apparent in this facies (E1 and E2 ; Figure 3). Detail of this facies (Event deposits) will be described after.

Delta plain deposits (core depths : HYR-1, 0.13-0 m ; HYR-2, 0.28-0 m ; HYR-5, 0.60-0 m ; HYR-8, 1.54-0.55 m)

The delta plain deposits (DP in Figure 3) comprise silt layers with organic material. On the upthrown side, EC shows about 0.1 mS/cm, whereas, on the downthrown sde (HYR-8), EC is 0.1-1.2 mS/cm. This was previously interpreted as delta plain facies (Sugai et al., 1998a) because it overlies delta front deposits. The sediments were dated at 673-911 cal BP (core

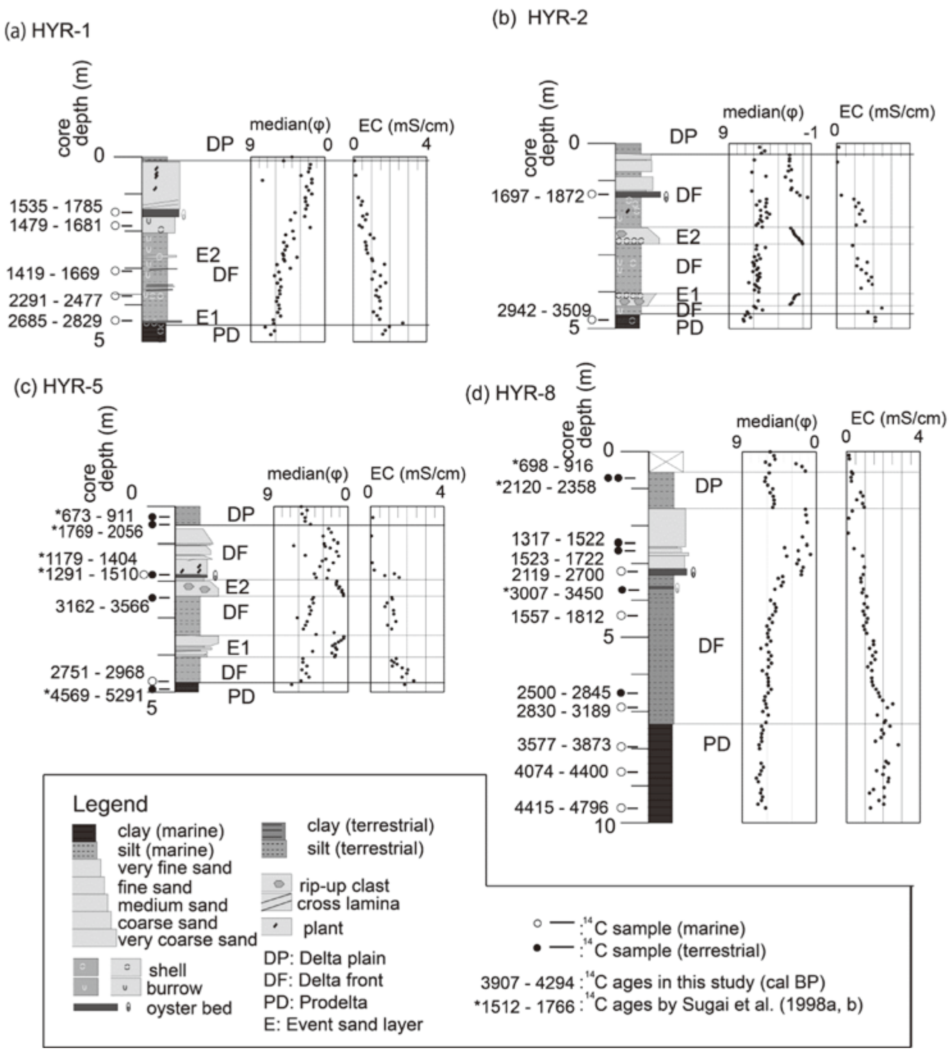

Figure 3 Core analyses results

HYR-5), and 698-916 cal BP (core HYR-8).

Event deposits (core depths : HYR-1, 4.52-4.47 m, 2.72-2.67 m ; HYR-2, 4.40-3.71 m, 2.73-2.27 m ; HYR-5, 4.06-3.48 m, 2.42-2.20 m)

For HYR-2, 3, 5, this facies consists of two sand layers sandwiched between lower delta front sandy silt deposits (E1 and E2 ; Figure 3). Median grain size is 0 φ to 2.0 φ. Lowest part of this facies has erosional contact. Rip-up clasts and shell fragments are apparent in this facies. E1 shows reverse grading, whereas E2 normal grading. For HYR-1, E1 consists of silt layer with shell fragment, whereas E2 fine sand layer with shell fragment showing upward fining. This facies is interpreted as event deposits based on erosional contact and shell fragment suggesting temporal strong stream.

5. Depositional Process of upper Holocene sequence and Timing of strong stream events

Gologic cross-section across the Kuwana fault shows typical deltaic sediments were deposited in this area (Figure 4). However, E1 and E2 indicate two strong stream evens occurred under the quiet condition during the deposition of lower deltafront sandy silt. Strong stream is considered to be triggered by flood, storm, or tsunami.

Estimated age range of two strong stream events is shown in Figure 5. The calendar ages obtained from core HYR-1 are 2,685-2,853 cal BP just below E1, 2,291-2,477 cal BP above E1, 1,419-1,669 cal BP below E2, and 1,479-1,681 cal BP above E2. Thus, for core HYR-1, E1 and E2 are interpreted to have been deposited 2,800 to 2,300 years ago and 1,600 to 1,400 years ago, respectively.

The calendar ages obtained from core HYR-2 are 2,942-3,509 cal BP below E1, and 1,697-1,872 cal BP above E2. Thus, for core HYR-2, E1 and E2 are interpreted to have been deposited 3,500 to 1,600 years ago, respectively.

The calendar ages obtained from core HYR-5 are 2,751-2,968 cal BP below E1, and 1,291-1,510 cal BP above E2. Thus, for core HYR-5, E1 and E2 are interpreted to have been deposited 3,000 to 1,300 years ago, respectively.

These data suggests that E1 and E2 can be correlated from core to core, and that two strong stream events occurred, 2,800 to 2,300 years ago, and ca. 1,700 years ago, respectively.

Based on the possibility that E1 can be correlated with previously known faulting event on the Kuwana fault (Naruhashi et al., 2008 ; Figure 5), one of the possibilities is that E1 is tsunami deposits caused by faulting on the Kuwana fault. However, strong stream can be caused by other phenomena (e.g. tsunami by the faulting on another active fault and/or ocean-trench (Nankai Trough) earthquake ; storm ; flood). Thus, determination of the cause of these two strong stream events is difficult at this moment.

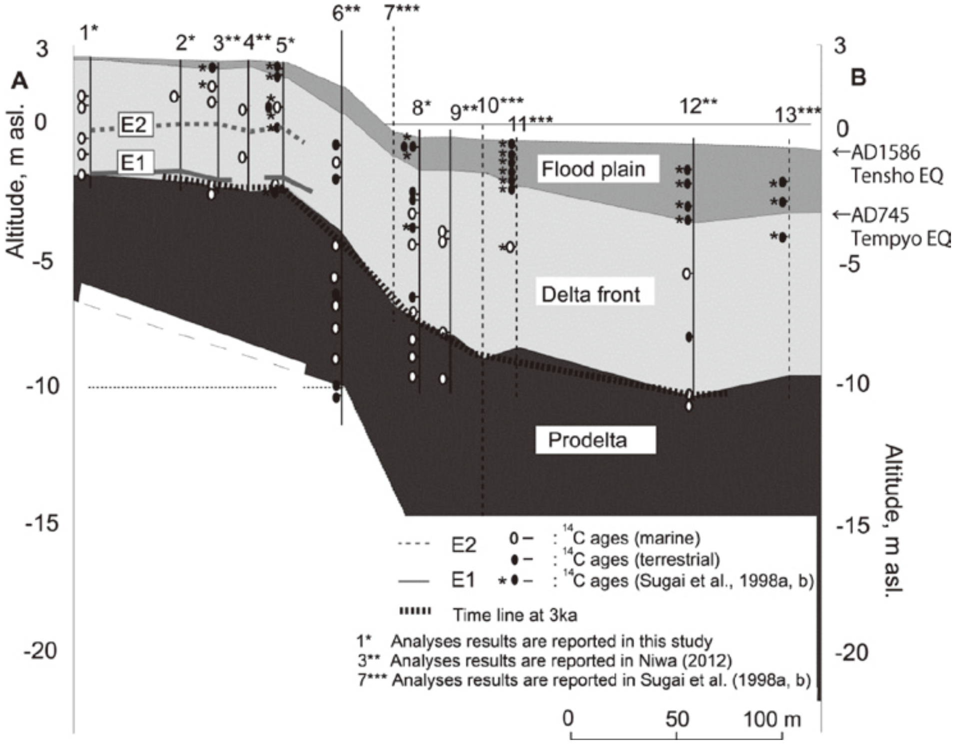

Figure 4 Geologic cross-section across the Kuwana fault (after Sugai *et al.*, 1998a, b)

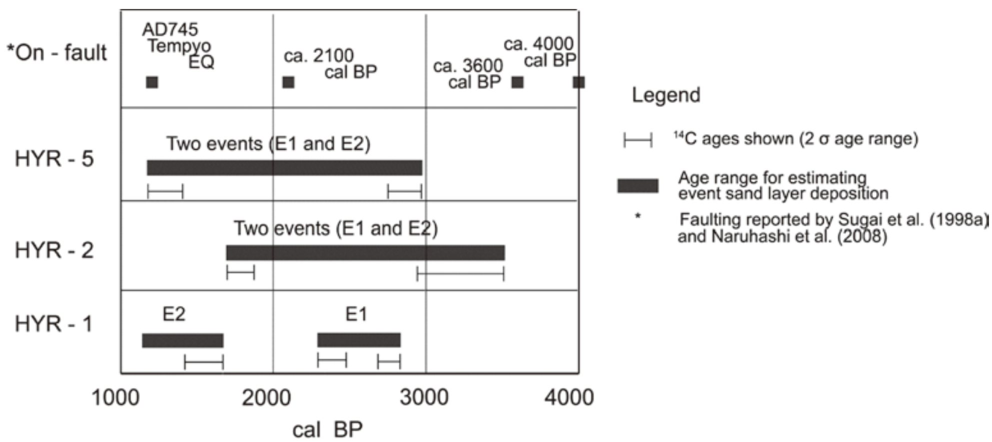

Figure 5 Timing of strong stream event

Identification of tsunami deosits and more detail chronological constraint is future subjects for understanding paleoseismicity in the coastal area, where tsunami can be caused by not only ocean-trench earthquakes but also faulting on the submarine active faults.

6. Conclusion

This paper reports the following.

1. We identified two event sand layers (E1 and E2, from lower to upper, respectively) in the lower deltafront sandy silt from upthrown side of the Kuwana fault.

2. Based on radiocarbon dating, E1 and E2 are considered to have deposited 2,800 to 2,300 years ago, and ca. 1,700 years ago, respectively, although determination of the cause of these two strong stream events is difficult at this moment.

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