Study of a Burial Model of a Shallow Submarine Active Fault Scarp: An Example from the Kuwana Fault, Central Japan

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Abstract

This study proposed a burial model of shallow submarine fault scarp which produced by the Kuwana fault whose event horizons were obtained in Naruhashi et al. (2008). We examined whether the change in grain size composition and the initial magnetic susceptibility of cores could be used as the proxy showing faulting events. Strata around the shallow marine reverse fault have two kinds of characteristic facies each of co-seismic event horizon and horizon corresponds to post-seismic burial processes, and both horizons form one sequential unit. By verifying grain size composition and depositional rates, we showed that burial process of the fault scarp start from foot of the scarp to distance, and clinoforms are added to the downthrown side gradually with a fault scarp planarization.

Key words: active fault, grain size, initial magnetic susceptibility, Kuwana fault, marine sediments

Introduction

To construct the repetition model of large-scale earthquakes produced by active faults, it is important to reconstruct earthquake recurrence intervals as precisely as possible for a long term. It is necessary to establish the method of reading environmental changes that show a past fault activity from sedimentary strata. We have tried to reconstruct Holocene fault paleoseismicity for the Kuwana fault of the Yoro fault system with high activity. Naruhashi et al. (2010) suggested a burial model of the fault scarp neighborhood according to co-seismic and post-seismic environmental changes chiefly presumed from depositional rates based on a large number of AMS14C ages. This study especially focuses on changes in grain size composition, and indicates a more exquisite burial model of submarine fault scarp from a geomorphological aspect.
Kuwana fault and its activity

The Kuwana fault is a reverse fault that cross the Holocene delta formed by the Kiso River at the southwestern margin of the Nobi Plain (Fig. 1). Holocene shallow marine deposits thick in the study area because of the growing accommodation (depositional rate is approximately 1 mm/y: Sugai and Sugiyama, 1999), post-glacial transgression and the huge amount of the clastic materials supply by the Kiso River that flows in the Central Mountain range with the world's largest denudation rate (Ohmori, 1983). Holocene delta around the study area is mainly composed of sand and silt-clay. The formation process is researched by Yamaguchi et al. (2003) and Ogami et al. (2009). The above-mentioned geomorphological environment has the favorable condition in detecting paleoseismic environmental changes for a long period from strata.

For the Kuwana fault, Naruhashi et al. (2008) tried to reconstruct Holocene activity on the basis of 82 AMS 14C dates, obtained from drilling cores that also analyzed in this study. That is, to detect the timing of each faulting event more precisely, we compared the change of depositional rates of cores of both the subsided (footwall) and uplifted (hanging wall) side. Based on this interpretation, five probable paleoseismic events (E3-E7) were detected for the period between 7,000 and 2,000 years ago as stepwise changes of depositional rate on the both sides of the fault.

Core samples and analysis method

Samples were obtained from the upper parts of four sediment cores, each with a diameter of 65 mm, extracted across the Kuwana fault by the Active Fault Research Center (AFRC), in the Yuriage district, Kuwana City, central Japan (Fig. 1). Core number 200 (50-m long, upper 35 m analyzed) and number 275 (40-m long, upper 31 m analyzed).
are on the downthrown side of the Kuwana fault, whereas number 350 (21-m long, upper 18 m analyzed) is on the upthrown side (Fig. 2).

In this study, grain size composition and initial magnetic susceptibility of the core sediments were analyzed. Grain size was analyzed at 5–10-cm vertical intervals along the core by laser diffraction (SALD-3000S particle size analyzer, Shimazu Corporation). A total of 1,198 samples were obtained from the four cores. As for initial magnetic susceptibility, 1,030 samples in total were measured at intervals of 5-cm. The unit of measurement is $10^{-3}$ SI units.

![Image](image_url)

**Fig. 2.** Geological cross section and migrated cross section of the reflection survey (modified after Naruhashi et al., 2010).

**Results**

Whether grain size composition and initial magnetic susceptibility were effective as the index of paleoseismic events, that obtained in Naruhashi et al. (2010), each annual changes graph are plotted by using the depositional curves (Fig. 3A, B) to verify (Fig. 4a-c). In addition, event horizons (E3-E7) are indicate by solid lines, and horizons on downthrown side in which depositional rates increase are indicate by shaded region (E3-E7).
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Grain size (median)

The changing trend through the entire core of grain size can be described as follows. The median of grain size in cores shows fluctuations with an intense serration in during relative sea-level highstand between 7,000 and 2,000 years ago (Fig. 3A). It stabilizes in transgression between 7,000 and 3,000 years ago, then, intensify rapidly after the delta front reached study area, grain size scale down again after emerging of the site. These changes harmonize with general depositional sequence of the river (Masuda, 2000) superior delta during the post-glacial.

The following some points can be pointed out as more detailed features about grain size changes. On the downthrown side, grain size increases spike-like rapidly on event horizons, then it becomes small once on upper layer; thereafter coarsens upward and becomes small again. Latter changes form a sine-wave pattern. That is, characteristic unit is formed both event horizon and horizon in which depositional rates increase, and it presumed corresponding to one earthquake event. On the upthrown side, although it is not clear on the corresponding horizon in which depositional rates of downthrown side increase, the coarsening-upward is shown around event horizons.

Sorting

Sorting in each core sediments is shown similar changes to the median of the grain size into perspective, and both values fluctuate to the serration intensely in the transgressive stage. It is 4,000-3,000 years ago when sorting improves most on the downthrown side, and agrees to time when grain sizes diminish most.

For sorting, spike-like changes are admitted at a lot of event horizons on the
Fig. 4. Annual changes of grain size (median), sorting and initial magnetic susceptibility of cores. (a) No.200 core. (b) No.275 core. (c) No.350 core.
downthrown side as well as grain size composition. Moreover, ‘sine-wave patterns’ are shown on horizons in which depositional rates increase.

In No.350 core on the upthrown side, though characteristic changes cannot be confirmed on horizons in which depositional rates increase, the tendency to which sorting worsens is admitted around event horizons.

**Initial magnetic susceptibility**

Initial magnetic susceptibility in each core is shown similar changes to the median of grain size and sorting into perspective and each value fluctuate consistent to the sea level changes in the post-glacial. The initial magnetic susceptibility reflects increase and decrease of a magnetic mineral and the tephra, etc. (Torii and Fukuma, 1998)

Intense spike-like increases are admitted around each event horizons of E4-E7 on the downthrown side, and it increases rapidly around E3. Increases are rapidly seen in E6-E4 also on the upthrown side. However, it differs from the grain size composition, changes in upper parts (horizons in which depositional rates increase) of event horizons are not able to recognize. So that it is shown in such spike-like changes, initial magnetic susceptibility is supposed that it differs from grain size composition and sorting, and the characteristic changes after the earthquake event is caused in sediments for a very short term.

**Burial model of the submarine fault scarp in the inner bay**

The burial process of the shallow submarine fault scarp on the reverse fault was modeled based on changes in grain size composition, initial magnetic susceptibility and depositional curves (Fig. 5). The model shows a sequence corresponding to one earthquake event. After the vertical faulting event, rough deposits including a lot of magnetic minerals comparatively are transported along with co-seismic sediment gravity flows. The former is indicated by spike-like changes in initial magnetic susceptibility on faulting event horizons (solid lines in Fig. 4a-c), As for the latter is indicated by spike-like changes of very fine sands-medium silts in grain size composition and initial magnetic susceptibility. Because this symfaulting sedimentation is seen equally on both No.275 and No.200 cores, it is presumed that sedimentation occurred wide-ranging and uniformly.

And then, in the burial process of the fault scarp, both grain size composition and sorting on the downthrown side that synchronize with increases of depositional rates in the shallow marine bottom, suggest that different materials was gradually supplied than usual. That is, on horizons in which depositional rates increase relatively (shaded regions in Fig. 4a-c) grain size coarsens as gradually as facies of delta front, and the sorting increases. The coarsening-upward can be clearly confirmed in changes of median. Afterwards, grain size shows fining-upward gradually with the decrease of depositional rates, and sorting decreases. Burial sequence totally indicates ‘sine-wave patterns’.
Consequently, in grain size composition and sorting, there are two patterns changes on each of faulting event horizons and horizons in which depositional rates increase. It is interpreted that above-mentioned two patterns of changes reflect the environmental changes and burial process afterward. That is, comparatively coarse and bad sorting deposits flowed rapidly in immediately after the earthquake, and then, on the downthrown side, the depositional center moves gradually from nearby fault scarp to distance, and clinoforms are added to the downthrown side gradually with a fault scarp planarization. In other words, it is thought that the fault scarp is buried like a
progradation apparently. This result shows the possibility that two paleoseismic horizons can be detected by sedimentary analysis of the nearby shallow submarine fault. These horizons are true event horizon and apparent event horizon which corresponding the post-seismic burial process.

However, above-mentioned co-seismic changes and subsequent burial process are recognized clearly on No.275 core which locates near the fault scarp, on No.200 core which locates left from fault scarp by about 100m, some of them are indistinct. We supposed this reflects the difference according to a topographical condition of distance from the fault scarp.

Conclusions

This study assumed the Kuwana fault to be an example, and analyzed the change of grain size composition and initial magnetic susceptibility of cores mainly. A burial model of shallow submarine fault scarp on the reverse fault is proposed in which comparing each of results and depositional rates of cores. The following results were obtained.
1. On faulting event horizons detected by Naruhashi et al. (2008), it is suggested that grain size (median), sorting and initial magnetic susceptibilities of cores undergo characteristic changes.
2. Initial magnetic susceptibility tends to increase spike-like around earthquake event horizons.
3. On the downthrown side, grain size and sorting indicate characteristic changes on both event horizons and upper horizons in which depositional rates increase. That is, grain size and sorting increases spike-like temporarily on event horizons first. And then it becomes small once on upper layer, thereafter coarsens upward (sorting becomes large) and becomes small again ('a sine-wave pattern').
4. In strata around the shallow marine reverse fault, there are two kinds of characteristic facies each of co-seismic event horizon and horizon corresponds to post-seismic burial process, and both horizons form one sequential unit.
5. We supposed that the burial process of the fault scarp start from nearby the scarp, and the downthrown side is buried like a progradation apparently.

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