Cross-Scale Modeling of Great Earthquake Cycles: Methodology, Postseismic Relaxation, Maximum Magnitudes

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We present details of a cross-scale thermomechanical model developed with the aim of simulating the entire subduction process from earthquake (1 minute), postseismic processes (minutes to years), seismic cycle and multiple seismic cycles (centures to milleniums) to tectonic evolution at million years' time scale. The model employs elasticity, non-linear transient viscous rheology, and rate-and-state friction. It generates spontaneous earthquake sequences, and, by using an adaptive time-step algorithm, recreates the deformation process as observed naturally over single and multiple seismic cycles.

A developed technique was used to model postseismic relaxation after great subduction earthquakes and for estimation of the maximum magnitudes of the earthquakes in subduction zones.

The set of 2D models is used to study effects of non-linear transient rheology on postseismic processes after great earthquakes. Models predict that viscosity in the mantle wedge drops by 3 to 4 orders of magnitude during the great earthquake with magnitude above 9 due to the power-law creep rheology (major factor) and transient dislocation creep based on experimental data and theoretical mineral physics considerations. This results in significantly different spatial scale and timing of the relaxation processes following the earthquake than it is currently believed. Our model produce large postseismic creep due to visco-elastic relaxation in the mantle wedge that shows up in surface deformation similar to the classical afterslip and therefore can be misinterpreted as an afterslip. The model fits well the GPS data for postseismic slip of Tohoku 2011 earthquake in the time range of 1 day-4 years.

Developed technique is also applied to study key factors controlling maximum magnitudes of earthquakes in subduction zones. Our models demonstrate that maximum magnitudes of the earthquakes are exclusively controlled by the factors that increase rupture width. These factors are: low slab's dipping angle (the largest effect), low friction coefficient in subduction channel (smaller effect) and high subduction velocity (the smallest effect). In agreement with observations, our models also suggest that the largest earthquakes should occur in subduction zones with neutral (most frequently) or moderately compressive deformation regimes of the upper plate. This is a consequence of the low dipping angles and low static friction coefficients in the subduction zones with largest earthquakes, rather than a reason for the largest earthquakes. The predicted maximum magnitudes for the subduction zones of different geometries are consistent with the observed magnitudes for all events.

Keywords: earthquake modeling, seismic cycle, postseismic relaxation, great earthquakes, maximum magnitude

Numerical simulation of the drag force from the mantle convection on the deformation pattern of the northeastern margin of the Tibetan Plateau

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Based on the recent observation and research results, including lithosphere velocity, rheological structure and crustal deformation, we established a 3D finite element model of the northeastern Qinghai Tibet Plateau, in which, the control effect, consist of the plateau gravity, block horizontal interaction, the main active fault, drag force from the mantle convection and some other internal and external conditions are considered. The simulation results are shown as follows: Continuous deformation is the main characteristic of current tectonic activity in northeastern margin of the Tibetan Plateau; Block horizontal interaction, plateau accumulated gravity, especially small-scale mantle convection drag force have important influence on the characteristics of surface deformation; Taking into account the view of the coupling of lithosphere / asthenosphere and decoupling of upper mantle, we put forward the rheological experiment on rock mechanical properties of the upper mantle decoupling mechanism, considering intensity factor ratio and coefficient of viscosity, we find that the simulation results is well agree with observation of GPS. The simulation results further support coupling mechanism of the northeastern margin of the Qinghai Tibet Plateau deformation; meanwhile, the calculation method of the mantle convection drag force is proposed, i.e., Transverse inhomogeneity of rheological properties of lithosphere at different block should be taken account in the calculation.

Keywords: northeastern margin of the Tibetan Plateau, the mantle convection drag force, Numerical simulation

Influence of fault surface condition on slip stability in large-scale biaxial friction experiment

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Slow slips and/or foreshocks preceding large earthquakes were often observed (e.g. Bouchon *et al.*, 2011; Kato *et al.*, 2012). To reproduce and investigate those activities in laboratory, we have conducted stick-slip experiments using large-scale biaxial friction apparatus at NIED (Fukuyama *et al.*, 2014). We used two rectangular metagabbro blocks as experimental specimen. The nominal contacting area was 1.5 m long and 0.1 m wide and the contacting surfaces were polished so that the undulation was less than 10 μm before the first experiment. We repeatedly conducted the experiments with the same pair of specimens, which means the fault surface continuously evolved with the frictional slip. The stick-slip experiments were conducted under the condition of constant normal stress of 6.7 MPa and loading rate of 0.01 mm/s. To monitor various phenomena on the fault, we installed dense arrays of strain gauges and PZT seismic sensors along the fault. In the first experiment, very few foreshocks were observed over the entire history of the experiment while precursory slow slips were observed before each main stick-slip event. We also found that both the occurrence location of slow slip and its occurrence time relative to the main rupture followed a mono-modal distribution at this initial stage. In later experiments, however, a variety of occurrence times and locations of slow slips was observed. The number of foreshocks also increased with the evolution of the fault surface, and the estimated hypocenters were located around the area where many gouge particles were generated during those experiments. To further investigate the relationship between foreshock activities and the existence of gouge, we focused on two experiments at the similar evolution stage but with different initial gouge conditions; one experiment was started with all previous gouge removed while the other was started with gouge from the previous experiment remained. Note that distribution of the gouge is not homogeneous but heterogeneous, because we did not give any operations to make the gouge layer uniform. First of all, both the number and magnitude of foreshocks were larger in the experiment with pre-existing gouge (denoted by PEG hereafter). In particular, relatively large number of big foreshocks were observed, which was revealed by a lower *b* value relative to the other. We also found that the maximum magnitudes of the foreshocks increased with the slip distance during the experiment without PEG, whereas they are almost constant in the experiment with PEG. The increase in the foreshock magnitude should be caused by an increase in the amount of newly generated gouge with slip. Therefore, these observations suggest that the upper limit of the foreshock magnitude is controlled by the gouge layer thickness. The gouge condition also affects how main event occurs. In the experiment without PEG, precursory slow slips were observed before every main event but foreshocks occurred only at the end of the nucleation process. The strain data suggested that foreshock occurrence in this condition requires relatively large stress concentration and subsequent stress release induced by the slow slip. In the experiment with PEG, on the contrary, no clear precursory slow slips were observed by the strain measurement. Instead, the number and magnitude of foreshocks increased towards the main event at an accelerated rate, which were confirmed by a decreasing *b* value. Spatiotemporal distribution of foreshock hypocenters suggests that foreshocks migrate and cascade up to the main event. We infer that heterogeneous gouge distribution caused stress-concentrated and destructive patches, which impeded slow and stable slip and activated foreshocks on the fault. These results confirm that fault surface condition affects the slip stability on it even under the same loading condition. They also suggest

that *b* value is a key parameter to explore the condition.

Keywords: Friction experiment, Slow slip, Foreshock, b value, Heterogeneity, Gouge

O(N) methods for spatiotemporal BIEM

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Recent progressions of seismic inversions has shown off the numerous results which cannot be explained by the ordinary source modelings, as seen in Tohoku 2011 and Kumamoto 2016. Particularly, the hierarchical features of fault sources have been clearly detected, e.g. hierarchical asperity distribution of Tohoku-Oki [Ide Aochi 2013] and the scaling of critical slip distance [Mikumo et al. 2003]. To get the whole descriptions, i.e. the theory of earthquakes, we must exceedingly develop the source modelings including those hierarchical behaviors.

The disturbance is the numerical cost. Boundary integral equation method (BIEM) has been widely used for the source modelings to resolve the highly nonlinear boundary conditions of the fault, but it is quite time-consuming method [Ando 2016]. The original BIEM needs the cost O(N^2L) (N:fault unit number, L fault length). For example, to resolve M4 (km) events on the M9 fault (400km), we need a Peta-scale simulater! Our aim is O(N) (theoretical fastest) algorithm to solve this problematic situation. We combine the fast domain partitioning method (FDPM)[Ando et al. 2009, Ando2016] and H-matrix method, then construct O(N) method for hyperbolic equations (FDPM=H-matrix). Furthermore, this O(N) method is principally faster than the corresponding finite element modelings.

In the presentation, we talk about how to apply the H-matrix method to elastic equations and the performance evaluations of the implemented algorithm. (i) How to achieve O(N); The elastic equations have the singular wave front, thus it is known that the naive applications of H-matrix method cannot achieve O(N) [Yoshikawa and Yamamoto 2015]. FDPM provides the key idea to solve this problem. The implementation is based on the physical fact that the kernel is regular along the ray, although the kernel is singular across the ray [Aki and Richards 1980]. Thus we can safely apply the H-matrix method if we can define the ray coordinate on the kernels. This abstract idea can be mostly implemented by the Adaptive cross approximations on Front domain (Domain F in the terminology of [Ando 2016]) and Tensor Cross Approximations on Near-field and Static regions (Domain I and S). Some approximations of causality is also required and we clear the problem analytically. (ii) Performance evaluations; We show the accuracy and cost of the proposed algorithm based on some case studies. FDPM=H-matrix has some crucial approximations of time-directions, thus we carefully review it and discuss the accuracy. The accuracy is quite good (with 0.3 percent error in some cases) if we sufficiently resolve the dynamic rupture. However, because of the causality conditions, O(N) looks not to be achieved rigorously in some cases and the cost reduction looks to draw back to O(N^1.5), thus we also discuss the alternative approximations to achieve O(N) even in these situations. The result of cost reduction is also discussed in the presentation.

If we use this FDP=H-matrix method, we can extensively study the complex fault modelings and examine the theoretical hypothesis of the source parameters as already referred. Because of the numerical costs, nonplanar features of faults(for example, damage zones, branchings and fractal fault roughness) are not so studied in the current stages compared with planar fault modelings. Those features are crucially related to the source parameters [Andrews 1976], thus this method will finally contributes to the study of observed source parameters of faults.

Keywords: Spatiotemporal BIEM, O(N) method, Dynamic Rupture of Faults, H-matrix

Renormalized source parameters on fractally rough faults

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Nonplanar properties of faults are considered to contribute to the fault source parameters [Andrews 1976, Scholz 2002]. However it is poorly studied compared to the comprehensive studies of planar fault models [Ando Yamashita 2007]. Partial reason is that the numerical cost of nonplanar faults is quite higher than the planar modelings. We proposed the O(N) method (FDP=H-matrix) in another presentation and solved this cost problem. So, we study the nonplanar effect of the fault using this method and report the result. We mainly focus on the fractal fault roughness universally observed in natural faults [Scholz 2002, Renard et al 2013].

The effect of the roughness is studied experimentally [Ohnaka 2002] and theoretically [Gold'stein and Mosolov 1991, Horvath Herrmann 1992], but those conclusions do not coincide with each other. The effect of fault roughness is well studied by the experiment of [Ohnaka 2002] and he found the critical slip scaling distance (Dc) linearly depends on the lower cutoff wavelength of the fractal scaling. This Dc scaling is consistent with the expected behavior of fault [Ide Aochi 2013]. However, the past renormalization group approach of the fractal fault predicted the different scaling of Dc [Gold'stein and Mosolov 1991]. The scaling exponent is smaller than the 0.5 (roughly 0.23 if we use the observed Hurst exponent 0.77 [Renard et al. 2013]) and quite weaker than the linear dependence as observed in experiments. Also, some theory asserts that terminal velocity becomes slower and slower if the earthquake becomes large [Horvath Herrmann 1992] but this prediction is inconsistent with the experiment [Ohnaka 2002] and simulations [Ide Aochi 2004, Dunham et al. 2011] It asserts the discrepancy of the interpretation from the actual physics behind the experiment and the lack of the theory. However, the studied parameter is still limited and the system size is not so large to discuss those scaling behavior.

Therefore, we present some results on dynamic rupture simulations on fractal rough faults using O(N) method. The current result is as follows. Dynamic rupture apparently propagates at sub-shear velocity but looks not so slower than the theoretical prediction; In some parameters where the crack with slip weakening friction does not stop spontaneously, we observed the subshear velocity of crack propagations. However, the terminal velocity looks faster than the theoretical prediction. Therefore, we constructed the estimation of the terminal velocity for the case where the Griffith energy becomes linearly depends on the crack sizes. This estimation predicts the the sub-shear terminal velocity. It looks consistent with our result and [Ide Aochi 2013]. The result of Dc scaling will be also discussed in the presentation.

Keywords: Rough Faults/ fractal roughness, source parameters, Dynamic Rupture of Faults

Dynamic rupture simulation for seismic hazard assessment: Application to the Yamazaki fault zone, central Japan

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In seismic hazard assessment, many earthquake rupture scenarios need to be weighted. For these scenarios, rupture area is one of the important factors, but the evaluation of the rupture area is unfortunately difficult before event. On the other hand, dynamic rupture simulations can calculate physically reasonable rupture processes based on fault geometries, stress conditions, and frictional constitutive laws. We propose dynamic rupture modeling for weighting of earthquake rupture scenarios, and apply the modeling to the Yamazaki fault zone, central Japan.

The Yamazaki fault zone is left-lateral strike-slip active fault in central Japan. We model three faults, the Ohara, Hijima, and Yasutomi faults in the northwestern part of the Yamazaki fault zone as a continuous vertical fault plane about 50 km long with surface rupture, based on the fault traces. The fault model is combined with assumption of stress field. Principal stresses are proportional to depth, based on the borehole data (Yamashita et al, 2004). A stress inversion result shows that the azimuth of the maximum principal stress is from N60°E to N100°E. We calculate dynamic rupture processes, using a finite-difference method (Kase and Day, 2006), to search the azimuth of the maximum principal stress and frictional coefficients most consistent with an observed left-lateral dislocation of about 2 m on the surface (Okayama Prefecture, 1996).

We simulate a variety of rupture processes on the Yamazaki fault zone, depending on parameters, but the simulation results show some characteristic rupture processes. For example, when the coefficients of friction are the same on the three faults, a rupture initiating on the Ohara fault propagates to the Hijima fault, but it terminates in the boundary between the Hijima and Yasutomi faults because of negative stress drop. When the coefficients of friction of the Yasutomi fault are less than those of the other faults, on the other hand, the rupture initiating on the Ohara fault propagates to both of the Hijima and Yasutomi faults, but the deep portion of the Yasutomi fault remains unrupture. These characteristics of rupture process can be useful information for weighting of earthquake rupture scenarios.

Keywords: dynamic rupture, Yamazaki fault, numerical simulation, seismic hazard assessment

MODELLING OF NEAR-FAULT EARTHQUAKE GROUND MOTION WITH EARTHQUAKE SIMULATIONS

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Engineering structures are usually designed on the base of accelerations derived from ordinary Probabilistic Seismic Hazard Analysis (PSHA) under the hypothesis of far-field conditions and further modified taking into account the local seismic response. As a consequence, a structure might not have proper safety levels if it is located close to an earthquake source. Despite the progress that has been accomplished so far by seismologist and earthquake engineers, the conducted research and papers in the literature highlighted that there could be a deficiency of seismic safety in near-field domains if the near-field seismic effects are not considered in the seismic design, as is the case of the Turkish seismic code.
The main purpose of this study is to analyze the near-field effects, focusing to evaluate ground shaking for specific fault configurations, specific source parameters and rupture process. For this reason, scenario simulations will be performed systematically to investigate the influence of different source parameters on the resulting near-source ground motion and to quantify the uncertainty in the employed source parameters and the associated variability in ground motion. The basis of the methodology is to generate a suite of synthesized seismograms from quasi-dynamic rupture models that use measurable or theoretically determined physical parameters that define fault rupture and control resulting ground motion.
Recent, well-instrumented earthquakes generated a large number of ground-motion recordings from sites close to the active fault. In these datasets, the observed variability of seismic ground motion meaningfully different from those far from the source not only in terms of intensity but also in terms of nature and topology. This contribution of earthquake source complexity to the ground-motion variability is generally thought to be significant, especially in the area near seismic sources. Only a few studies systematically investigated the influence of different source parameters on the resulting near-source ground motion. For that reason, there is a clear need to develop reliable synthetic ground motions or simulations reveal that not only influence of different source parameters on the resulting near-source ground motion but also capture different physical characteristic of near fields records both qualitatively and quantitatively.

Keywords: NEAR-FAULT EARTHQUAKE GROUND MOTION, EARTHQUAKE SOURCE PARAMETERS, SIMULATION OF STRONG GROUND MOTION, GREEN’S FUNCTIONS

Rupture process of the 2016 Meinong, Taiwan, earthquake and its effects on strong ground motions

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Meinong Taiwan earthquake occurred in the Meinong area of southern Taiwan on 6 Feb. 2016, but caused the most severe damages in Tainan. Large amplitude accelerations and velocity pulses in both EW direction and NS direction were recorded by strong motion stations in Tainan. To investigate the characteristics of strong motion distribution in Tainan, a joint source inversion was performed. The results of source process show that the rupture propagated from hypocenter toward northwest nearly along strike direction with a constant velocity close to shear wave velocity; the main rupture area occurred in the northwest of hypocenter and was close to Tainan; the radiation pattern of *S* waves generated from the main rupture area, which is dominated by oblique slips with large rake angle and small dip angle of faulting, and the small azimuth between rupture propagation direction and the direction of seismic ray, contributed jointly to the directivity effect observed in Tainan. Velocity pulses, having larger components along strike parallel direction than that along strike normal direction, recorded in Tainan during Meinong event, have important implications on the seismic design of tall buildings in near fault region.

Keywords: rupture process, rupture directivity effect

Super-shear fault rupture propagation during the 2016 Kumamoto earthquake (Mw7.1); Numerical tests and resolution

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I investigated the rupture process of the April 16, 2016 Kumamoto earthquake, using a seismic back-projection methodology (Pulido et al. 2008, Pulido 2016), and a dense array of near-source strong motion records from the K-NET/KiKnet networks. The main target of this study is to understand the evolution of the rupture velocity during fault rupture propagation. I selected all the KNET/KiKnet records of the mainshock within 100 km around the Hinet epicenter (112 stations), and used the fault-parallel component rotated from the horizontal components. I bandbass filtered the data between 5 to 10 Hz and calculated the envelopes of velocity time series. Envelopes were stacked within a horizontal grid mesh covering the regions around the Hinagu and Futagawa fault traces and beyond, to obtain a temporal and spatial image of rupture propagation. My back-projection results show that significant grid energy was released in a region spanning 43km length along the Hinagu (16km) and Futagawa (27 km) fault zones. Back-projection results show a bilateral fault rupture propagation along the Hinagu and Futagawa faults, characterized by a slow sub-Rayleigh rupture velocity of 1.4 ~ 1.7 km/s, for the first 5.5 seconds of imaged rupture (4~9.5s from the origin time, OT). The rupture propagation towards the NE (along the Futagawa fault) experienced a very rapid increase in rupture velocity by reaching a value ~1.4 times larger than the average S-wave velocity (Vrup= 4.7 km/s) at 9.5s from OT, and remained super-shear for approximately 4.5 s (9.5 ~14s from OT) until fault rupture arrest. I also imaged a clear sub-Rayleigh rupture propagation towards the SW along the Hinagu fault zone (Vrup= 3.1 km/s), from 11 to 14 seconds after OT. I performed several numerical tests to analyze the effect of station distribution and the and the ability of my back-projection method to resolve the rupture process. I also performed multiple tests using actual records of aftershocks of the Kumamoto earthquake to test the accuracy of my results. All these tests indicate that the super-shear rupture propagation during the Kumamoto mainshock is a robust feature of my imaging results.

Keywords: 2016 Kumamoto earthquake, super-shear fault rupture, strong ground motion, seismic back-projection

The cause of long-time-duration long-period ground motion observed in Hokkaido during off-Tohoku earthquakes

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We found a development of anomalously large and long-time-lasting long-period ground motions in the area around Ishikari, Hokkaido Japan, during off-Tohoku earthquakes. In order to clarify the generation mechanism of this anomalous wave, we conducted a set of numerical simulations of seismic wave propagation in realistic 3D heterogeneous subsurface structures by means of a finite difference method (FDM).

The anomalous long-period wave spreads Ishikari Basin and Teshio Basin, Hokkaido, was clearly observed for shallow earthquakes occurred off-Tohoku. The dense broadband records of Hi-net short-period seismographs after correcting the instrumental response showed that a large long-period ground motion (T=14~18 s) lasting more than 200 s appears in the region in Hokkaido. This long-period ground motion dominates in both horizontal and vertical components indicating dominance of surface waves propagating northward. Such anomalous wave did not appear obviously during the earthquakes away from the off-Tohoku region.

Based on the geophysical reflection and refraction experiments and analysis of the gravity data, it is known that deep (~10 km) tectonic basins extends from northern Hokkaido to the sea of southern Hokkaido toward the direction to off-Tohoku through the west of Hidaka Mountains. Thus, it is expected that such deep basin structure causes strong effect on the development of the anomalous long-period ground motions mentioned above.

To investigate the cause of the observed long-time-lasting long-period ground motions with interaction to the heterogeneous subsurface structure below Hokkaido in detail, we conducted a FDM simulation of seismic wave propagation using the OpenSWPC (Maeda et al., 2017). We used a realistic 3D subsurface structure model including topography, seawater, sediments and subducting Pacific plate. The result of the simulation demonstrated the development of the long-period ground motion in the area around Ishikari Basin and Teshio Basin which qualitatively reproduces the observed feature, however the duration of the simulated long-period ground motion was not long enough compared with the observation. By modifying the sedimentary structure where the P- and S-wavespeed of the sedimentary layers were replaced with much smaller values, we succeeded in obtaining much longer-time lasting long-period ground motions similar to the observation. The results of the simulation with snapshots of seismic wavefield at each time step and movies demonstrating clearly the process in which the surface waves generated above the epicenter were trapped and amplified in deep sediments at south off Hokkaido, and radiated the long-period motion to northward for a long time to develop a large and long-time-lasting long-period ground motion.

Keywords: Long-period ground motion, Numerical simulation, Surface wave, Long-time duration, Deep basin

Regional earthquake induction around the Korean Peninsula after the 2011 M9.0 Tohoku-Oki megathrust earthquake

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Megathrust earthquakes produce large permanent lithospheric displacements as well as strong transient ground shaking up to regional distances. The lateral permanent displacements construct stress shadows in a wide backarc region. The Korean Peninsula is placed in the far-eastern Eurasian plate that belongs to a stable intraplate region with a low earthquake occurrence rate and diffused seismicity, and is located in the backarc at ~1300 km in the west from the epicenter of the 11 March 2011 M9.0 Tohoku-Oki earthquake. The seismicity around the Korean Peninsula was increased significantly after the 2011 M9.0 Tohoku-Oki earthquake. Strong seismic waves cause large dynamic stress changes, incurring fluid migration and increasing pore fluid pressure in the media. The lithospheric displacements directing to the epicenter on the convergent plate boundary develop transient radial tension field over the backarc lithospheres. The seismic velocities in the lithosphere changed abruptly up to 2 % after the megathrust earthquake, which recovered gradually with time for several years. A series of moderate-sized earthquakes and earthquake swarms occur as a consequence of medium response to the temporal evolution of stress field. In particular, two strike-slip earthquakes with magnitudes of M_L5.1 and 5.8 occurred in the southeastern Korean Peninsula on September 12, 2016. The two events occurred within 48 minutes. The M_L5.8 earthquake was the largest event in the Korean Peninsula since 1978 when national seismic monitoring began. More than 500 aftershocks with local magnitudes greater than or equal to 1.5 followed the events for two months. The long-term evolution of seismicity is expected to continue until the ambient stress field is fully recovered.

Recurrence Pattern of Tsunami events of Nankai Earthquake recorded in lacustrine sediments along the eastern coast of the Kii Peninsula, southwest Japan.

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We studied on tsunami sediment in small lakes along the Nankai Trough for the reconstruction of prehistoric tsunami. Total 33 cores were collected from the three lakes named Ashihama-ike, Zasa-ike and Usuzuki-ike, which located on behind coastal ridge along the southeastern coast of Kii Peninsula.
These lakes preserved last 3500 years record of Nankai Earthquake tsunamis. Tsunami events are observed intervals of 3500-3000 yBP, 2700-2000 yBP and 1300-1000 yBP. Furthermore, each interval is composed 2-3 events that decrease in size. These recurrence mode of tsunami events indicate fractal-like patterns.

Keywords: Nankai Earthquakes, tsunami sediments, recurrence pattern

